# SIMULATION OF PROPULSION PLANT DYNAMICS AND THEIR EFFECT ON SPEED CONTROL

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# NAVAL POSTGRADUATE SCHOOL
## Monterey, California

# THESIS

SIMULATION OF PROPULSION PLANT DYNAMICS
AND THEIR EFFECT ON SPEED CONTROL

by

Tran-Van VAN

June 1974

Thesis Advisor: George J. Thaler

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

| REPORT DOCUMENTATION PAGE | | READ INSTRUCTIONS BEFORE COMPLETING FORM |
|---|---|---|
| 1. REPORT NUMBER | 2. GOVT ACCESSION NO. | 3. RECIPIENT'S CATALOG NUMBER |
| 4. TITLE (and Subtitle) Simulation of Propulsion Plant Dynamics And Their Effect on Speed Control | | 5. TYPE OF REPORT & PERIOD COVERED Master's Thesis; June 1974 |
| | | 6. PERFORMING ORG. REPORT NUMBER |
| 7. AUTHOR(s) Tran-Van VAN | | 8. CONTRACT OR GRANT NUMBER(s) |
| 9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Postgraduate School Monterey, California 93940 | | 10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS |
| 11. CONTROLLING OFFICE NAME AND ADDRESS Naval Postgraduate School Monterey, California 93940 | | 12. REPORT DATE June 1974 |
| | | 13. NUMBER OF PAGES 94 |
| 14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office) Naval Postgraduate School Monterey, California 93940 | | 15. SECURITY CLASS. (of this report) Unclassified |
| | | 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE |

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Propulsion-Plant

DSL/360 Language

Governor

Ship Speed Control

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The dynamics of a ship propulsion plant are modeled in an all digital simulation. This model is combined with that of a mariner hull. The behavior of the speed governor is studied, and an external feedback loop is added to provide direct control of ship speed.

DD FORM 1473, 1 JAN 73 (Page 1) EDITION OF 1 NOV 65 IS OBSOLETE S/N 0102-014-6601

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

# Simulation of Propulsion Plant Dynamics

# And Their Effect On Speed Control

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from the

NAVAL POSTGRADUATE SCHOOL
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## LIST OF DRAWINGS

## TABLE OF SYMBOLS

| | | |
|---|---|---|
| $X,Y,Z$ | : | System of reference axes fixed in the ship |
| $X_0,Y_0,Z_0$ | : | System of reference axes fixed in the ship |
| $m$ | : | Mass of ship |
| $\phi$ | : | Roll angle |
| $\theta$ | : | Pitch angle |
| $\psi$ | : | Yaw angle |
| $\delta$ | : | Rudder deflection |
| $K,M,N$ | : | Components of resultant total moment acting on a ship about the X,Y,Z axes. |
| $p,q,r$ | : | Components of resultant angular velocity of the ship about the X,Y,Z axes. |
| $I$ | : | Mass moments of inertia of a ship. |
| $Yv$ | : | Partial derivative of Y with respect to $v$ |
| $Y\dot{v}$ | : | Partial derivative of Y with respect to $\dot{v}$ |
| $Yr$ | : | Partial derivative of Y with respect to $r$ |
| $Y\dot{r}$ | : | Partial derivative of Y with respect to $\dot{r}$ |
| $Nv$ | : | Partial derivative of N with respect to $v$ |
| $N\dot{v}$ | : | Partial derivative of N with respect to $\dot{v}$ |
| $Nr$ | : | Partial derivative of N with respect to $r$ |
| $N\dot{r}$ | : | Partial derivative of N with respect to $\dot{r}$ |
| $n$ | : | Propeller angular speed |
| $Qe$ | : | Shafting torque |
| $Qp$ | : | Propeller reaction torque |
| $Kg$ | : | Reduction gear ratio |
| $Wf$ | : | Fuel flow rate |

| | | |
|---|---|---|
| W | : | Wake fraction |
| Ct | : | Thrust coefficient |
| Cq | : | Torque coefficient |
| T | : | Thrust |
| Q | : | T~~h~~orque |
| p | : | Water mass density |
| D | : | Propeller diameter |
| σ | : | Second modified advance coefficient |
| V | : | Ship speed |

## ACKNOWLEDGEMENT

The author wishes to express his sincere appreciation to Dr. George J. Thaler for the guidance, assistance and continuous encouragement during the pursuit of this study.

# I. INTRODUCTION

The propulsion system of a ship is a complex, nonlinear system with several internal feedback loops. The performance of the ship itself is dependent, of course, on the capabilities and limitations of the propulsion plant, which may limit overall ship performance so that the capabilities of the hull design are not realized.

The first objective of this thesis is to model, in detail, a typical ship propulsion system, and to simulate it in the digital computer.[1] After validation of the computer model a simulation of the Mariner hull is to be coupled to the propulsion plant so that control system studies may be undertaken. As part of the validation procedure, behavior of the shaft speed was investigated with and without the governor.

The second objective was to use the computer model as part of a ship feedback control system. For this purpose it was decided to explore the use of a feedback loop to maintain constant ship speed in turns.

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[1] IBM 360/67 DSL 360 LANGUAGE at W. R. Church Computer Center, Naval Postgraduate School.

## II. PROPULSION PLANT DYNAMICS

### A. SHIP PROPULSION EQUATIONS

The propeller angular speed is denoted by n.

The basic equation describing the angular acceleration of a propulsion shafting system is:

$$\Sigma Q = 2\pi I dn/dt$$

Where: $\Sigma Q$ = Summation of torque = Qe-Qp

I = Polar mass moment of inertia

n = Propeller angular speed

Qe = Shafting torque

Qp = Propeller reaction torque

then $$dn/dt = \frac{1}{2\pi I}\Sigma Q$$

For the typical gas turbine, the experimental data on the power turbine torque Qe versus the power turbine speed is shown in Fig. A1. The torque map of Fig. A1 allows the engine torque to be determined if the engine speed and fuel flow rate Wf are know. However, this torque representation is correct only for steady state contitions.

Propeller speed n(rps) is related to the engine speed N3(rpm) through the reduction gear ratio Kg

$$N3 = 60Kg.n$$

The block diagram for the ship propulsion system is given in Fig. A2.

The power turbine speed can be controlled by a governor acting on the gas flow. The changes in fuel flow and speed that occur can be

assumed small enough to permit the use of constant coefficients in the dynamic equations.

Using the time lag of the governor, $\tau$, the block diagram for the Governor is shown in Fig. A3,

Where: $n^*$ = Rotational speed order

$n$ = Rotational speed

ner = $n^* - n$ = Speed error signal

Kf = Fuel flow rate/RPM

$\tau$ = Time delay

Wf = Fuel flow rate

GOVERNOR = $Kf/(1+\tau S)$

Then the propulsion plant is shown in Fig. A4.

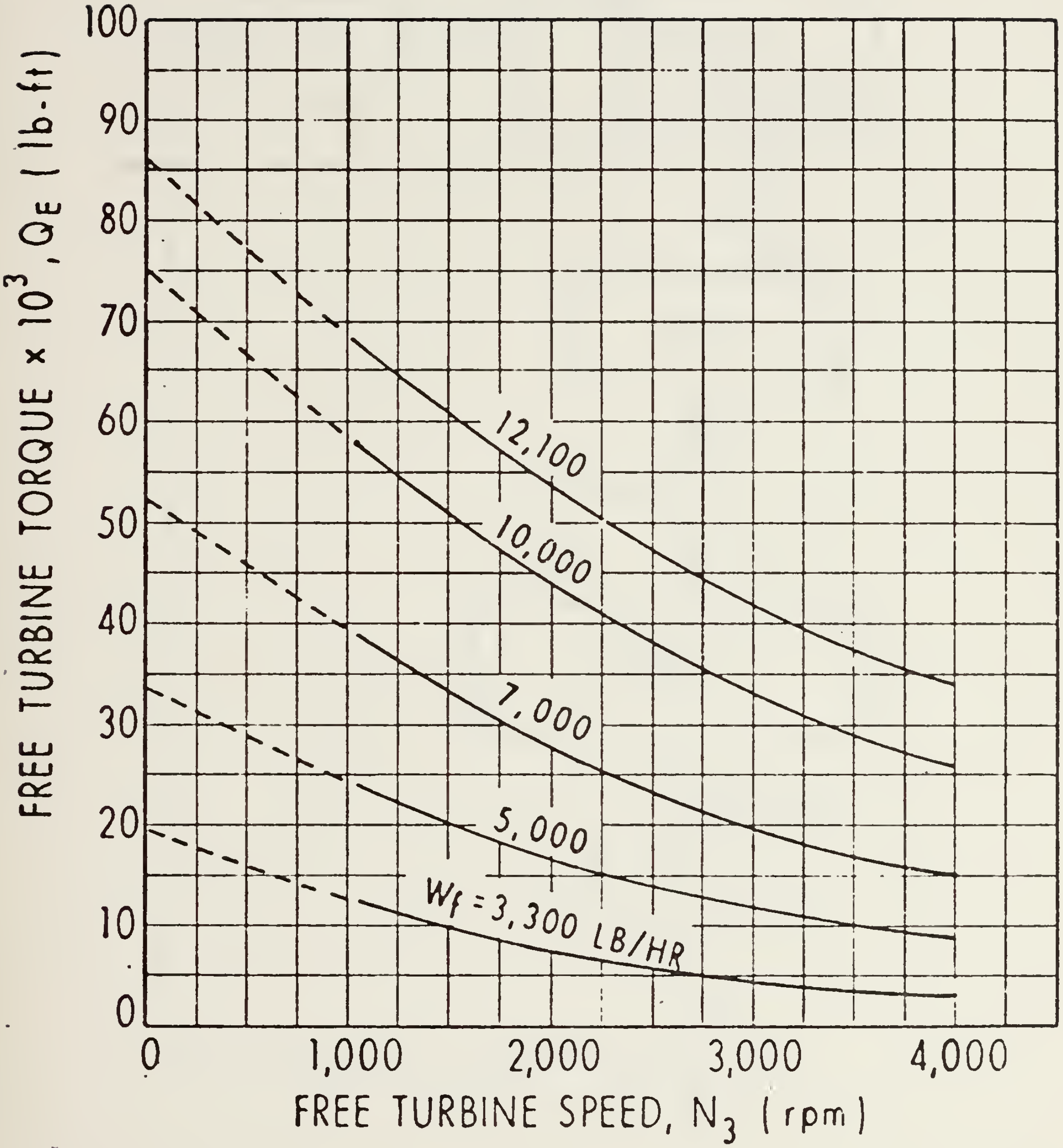



Figure A1. Engine Torque versus Engine Speed and Fuel Flow Rate

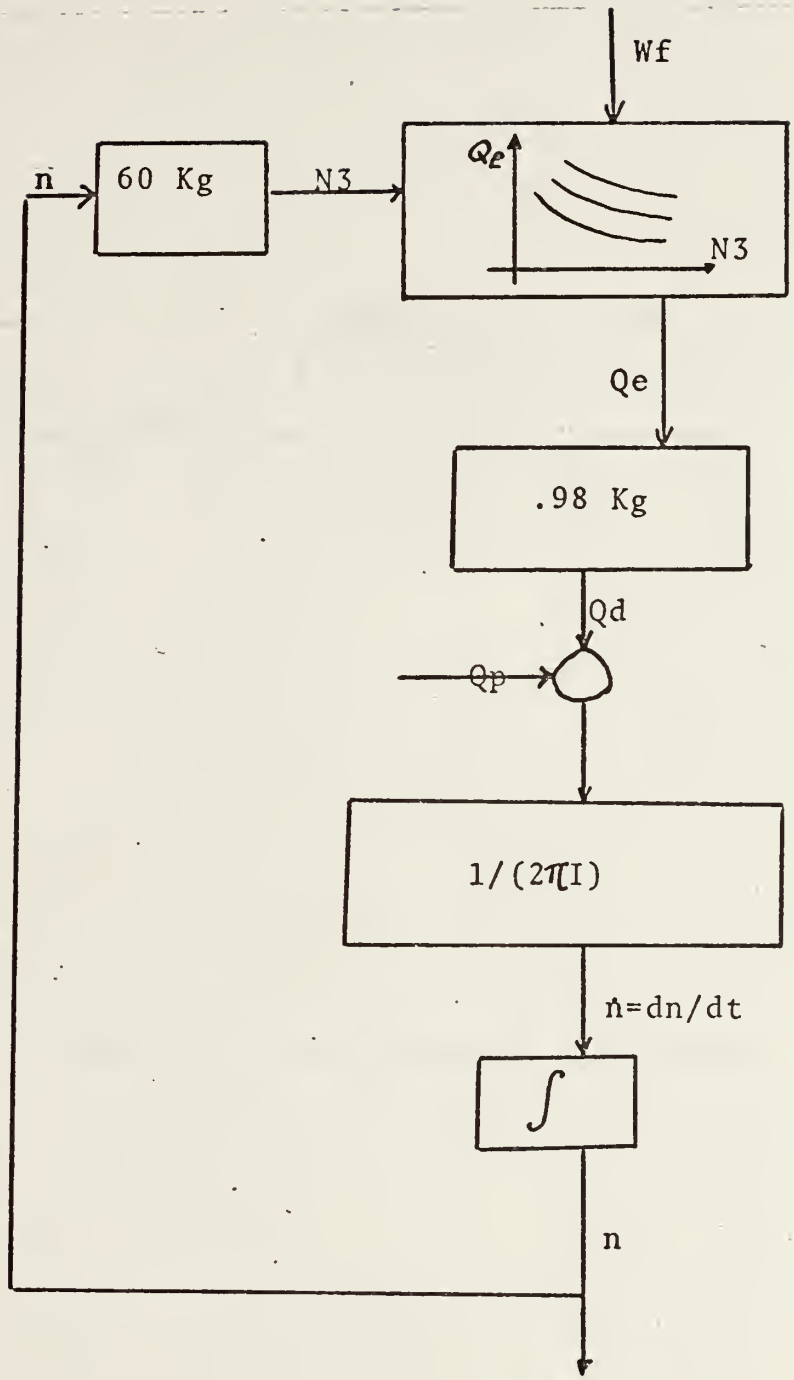



Figure A2. Block Diagram of Ship Propulsion System

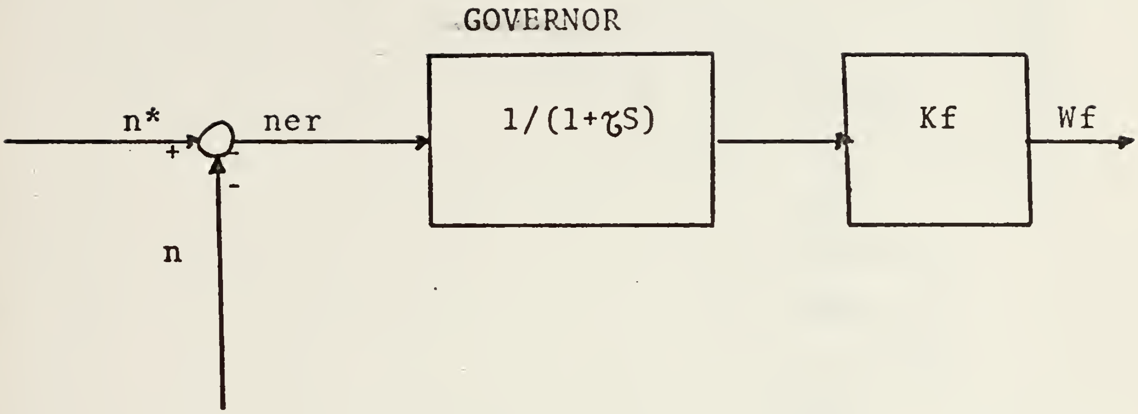



Figure A3. Block Diagram for the Governor.

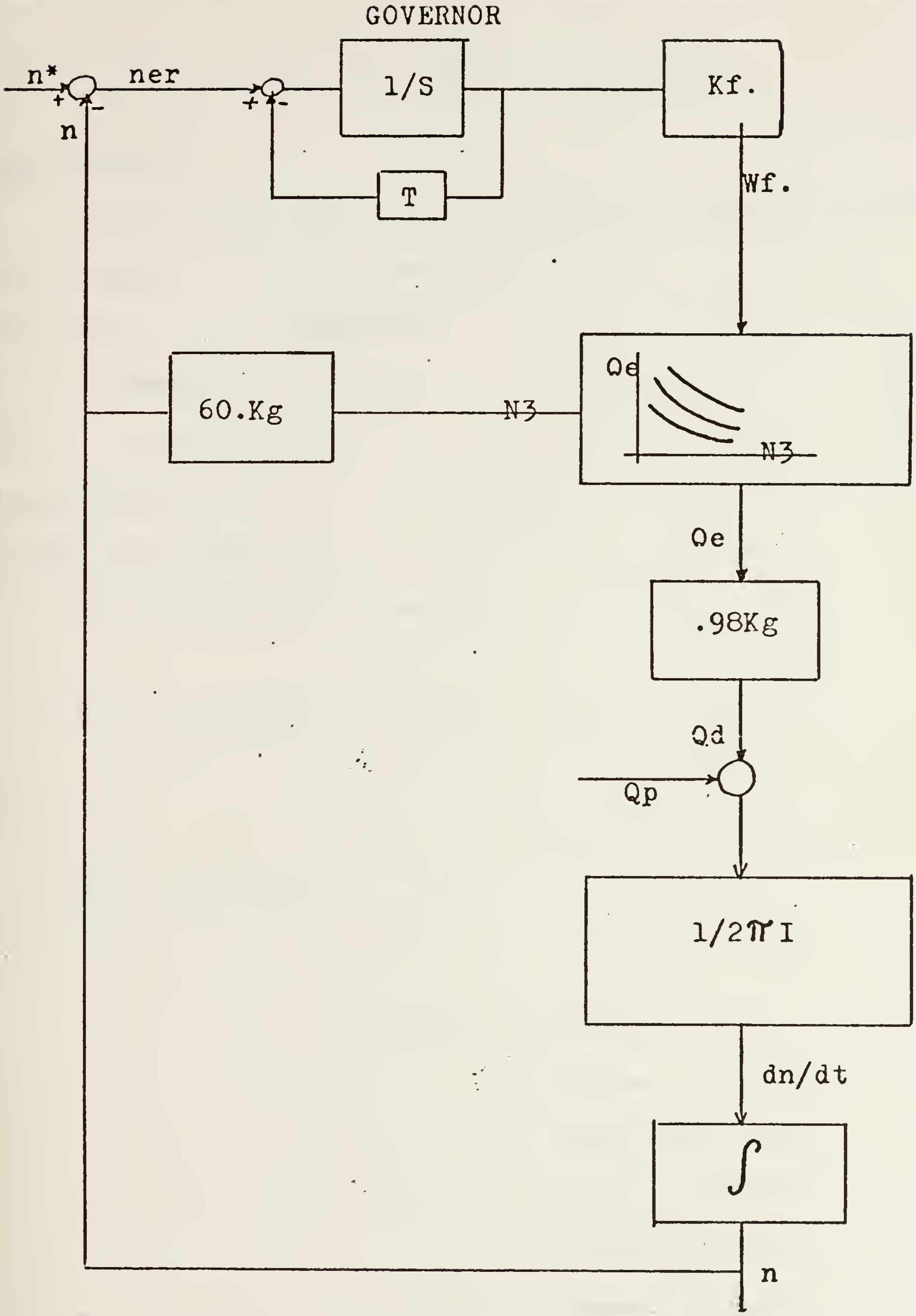



Figure A4. The Propulsion Plant with Governor

## III. HULL EQUATION AND SIMULATION

WAKE FRACTION: W

The difference between the ship speed and the speed of advance of the propeller Vp is called Wake speed.

The Wake fraction is defined as

$$W = (V-Vp)/V$$

thus $\quad Vp=V(1-W)$

THRUST COEFFICIENT: Ct

TORQUE COEFFICIENT: Cq

For the propeller in open water

$$Ct = \frac{T}{pD^2(Vp^2+n^2D^2)} \qquad (1)$$

$$Cq = \frac{Q}{pD^3(Vp^2+n^2D^2)} \qquad (2)$$

Where T = Thrust

Q = Torque

p = Water mass density

Ct = Thrust coefficient

Cq = Torque coefficient

D = Propeller diameter

From (1) and (2)

$$T = Ct.pD^2(Vp^2+n^2D^2)$$

$$Q = Cq.pD^3(Vp^2+n^2D^2)$$

The experimental data on the Wake fraction versus the speed of the ship is shown in Fig. B1.

The Thrust coefficient Ct and Torque coefficient Cq versus the Second modified advance coefficient are shown in Fig. B2 and Fig. B3.

Where $Vp = V(1-W)$

And $\sigma = (n.D)/Vp^2+n^2D^2)$

Total ship Resistance, Rt, is a computer look-up table giving Rt versus Ship speed V (fig. B4).

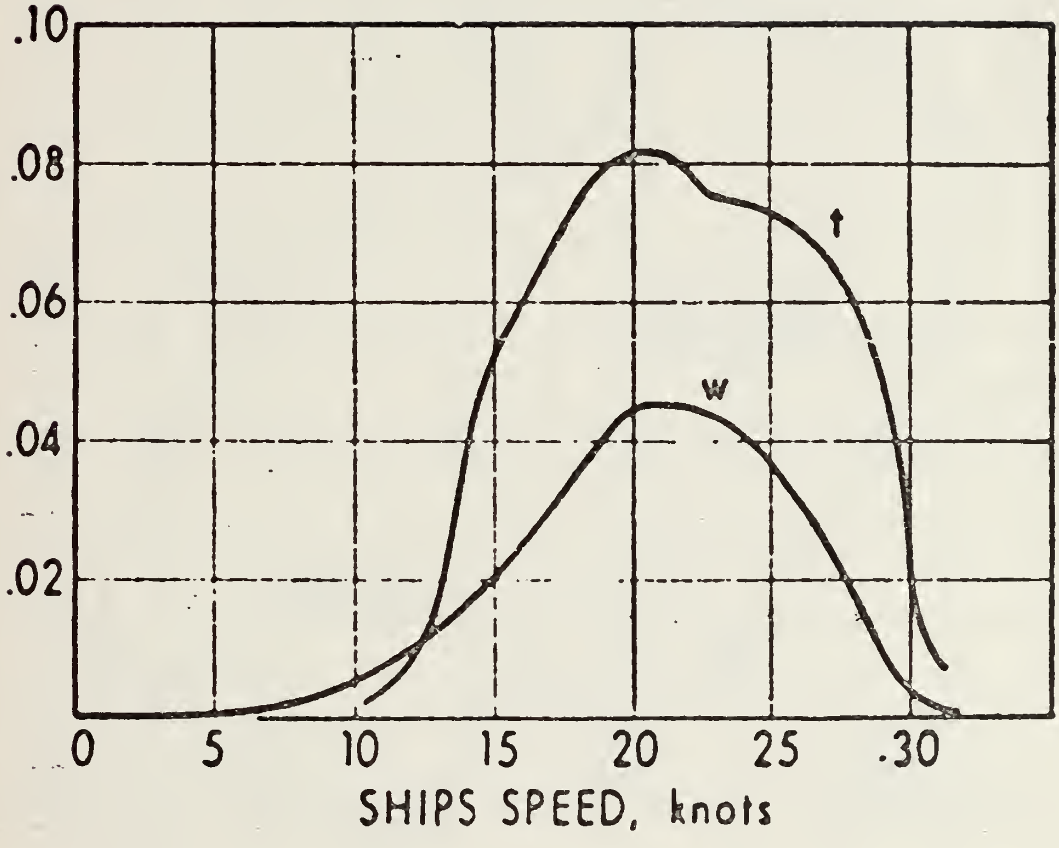



Figure B1. Wake Fraction and Thrust Deduction versus Ship Speed

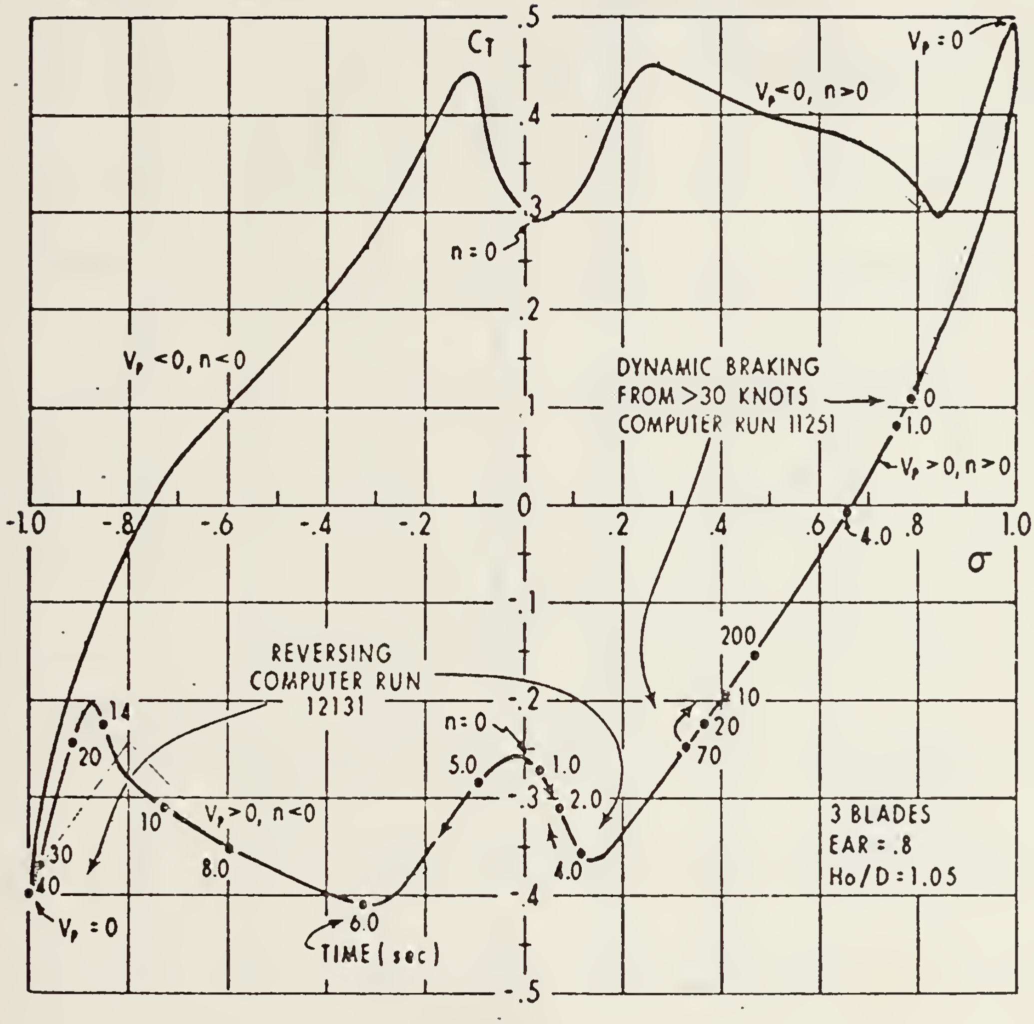



Figure B2. Thrusting Coefficient Ct versus Second Modified Advance Coefficient σ

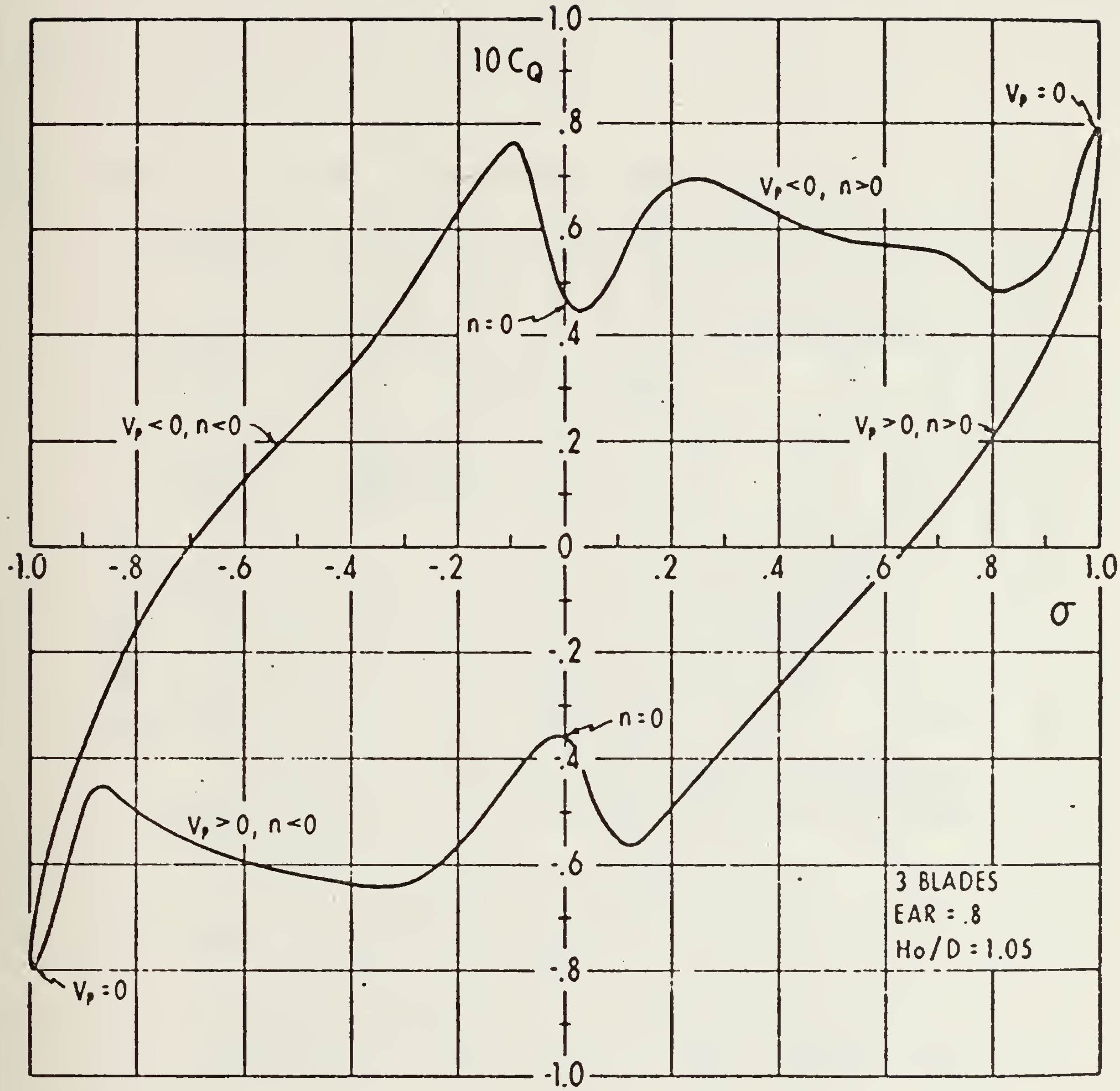



Figure B3. Torque Coefficient Cq versus Second Modified Advance Coefficient σ.

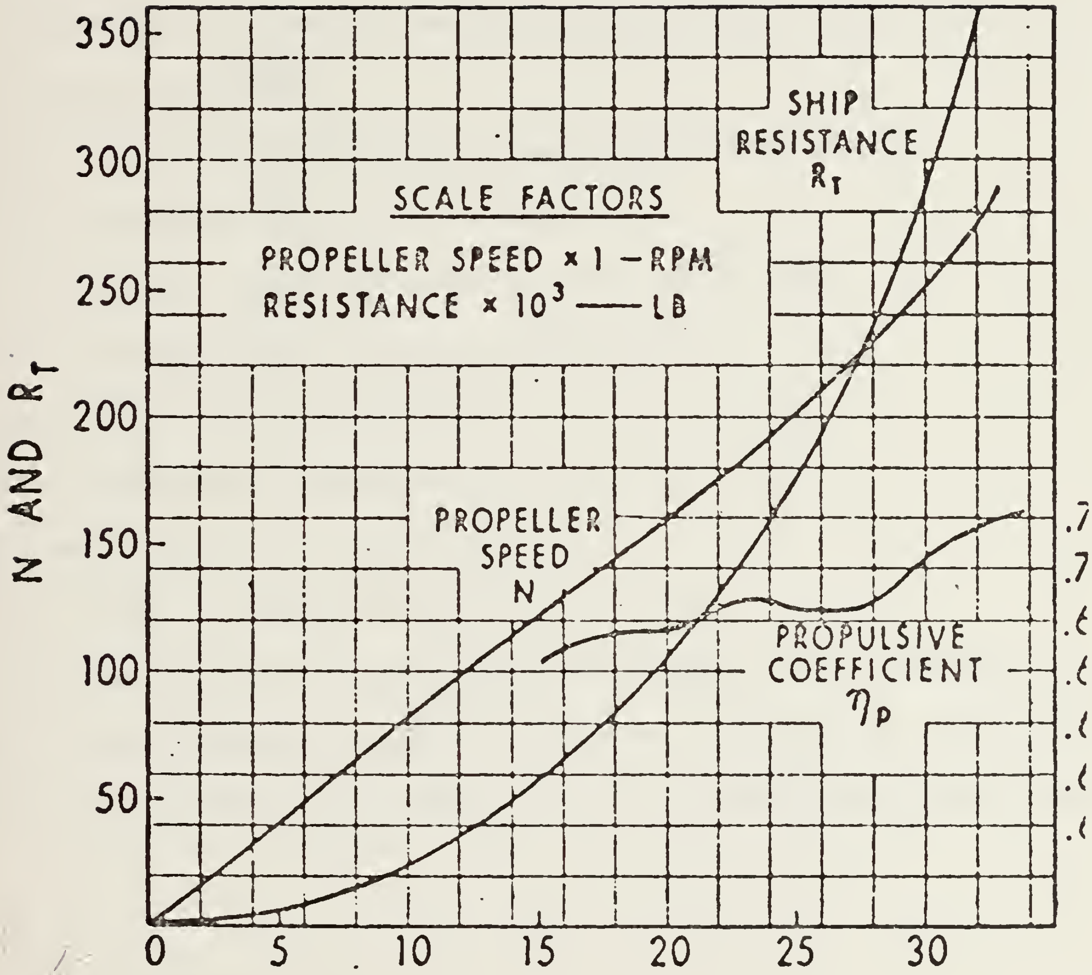



Figure B4. Ship Resistance versus Ship Speed V.

# IV. COMBINED PROPULSION PLANT AND HULL EQUATION

## A. POWER TURBINE WITHOUT GOVERNOR:

Nonlinear functions such as Wake fraction, Thrust deduction fraction, Thrust coefficient, torque coefficient, ship resistance and engine torque were stored in look-up tables during the computer solution.

Using the DSL/360 language these equations were solved by means of an integration and updating from table look-up every 0.1 sec until the steady state was reached.

Fig. B5. shows propeller shaft speed (rpm) versus time

Fig. B6. shows ship speed V versus time

Fig. B7. shows propeller action torque versus time

Fig. B8. shows shaft torque Qe versus time

Fig. B9. shows Cq versus time

Fig. B10.shows Ct versus time

For a step change in fuel flow rate

Wf = 7000. + 3000. step (0.0)

The shaft torque decreases and goes to steady state. The propeller action torque increases, overshoots at 10 sec. then goes to steady state. The propeller shaft speed increases, goes to steady state in about 80 sec.

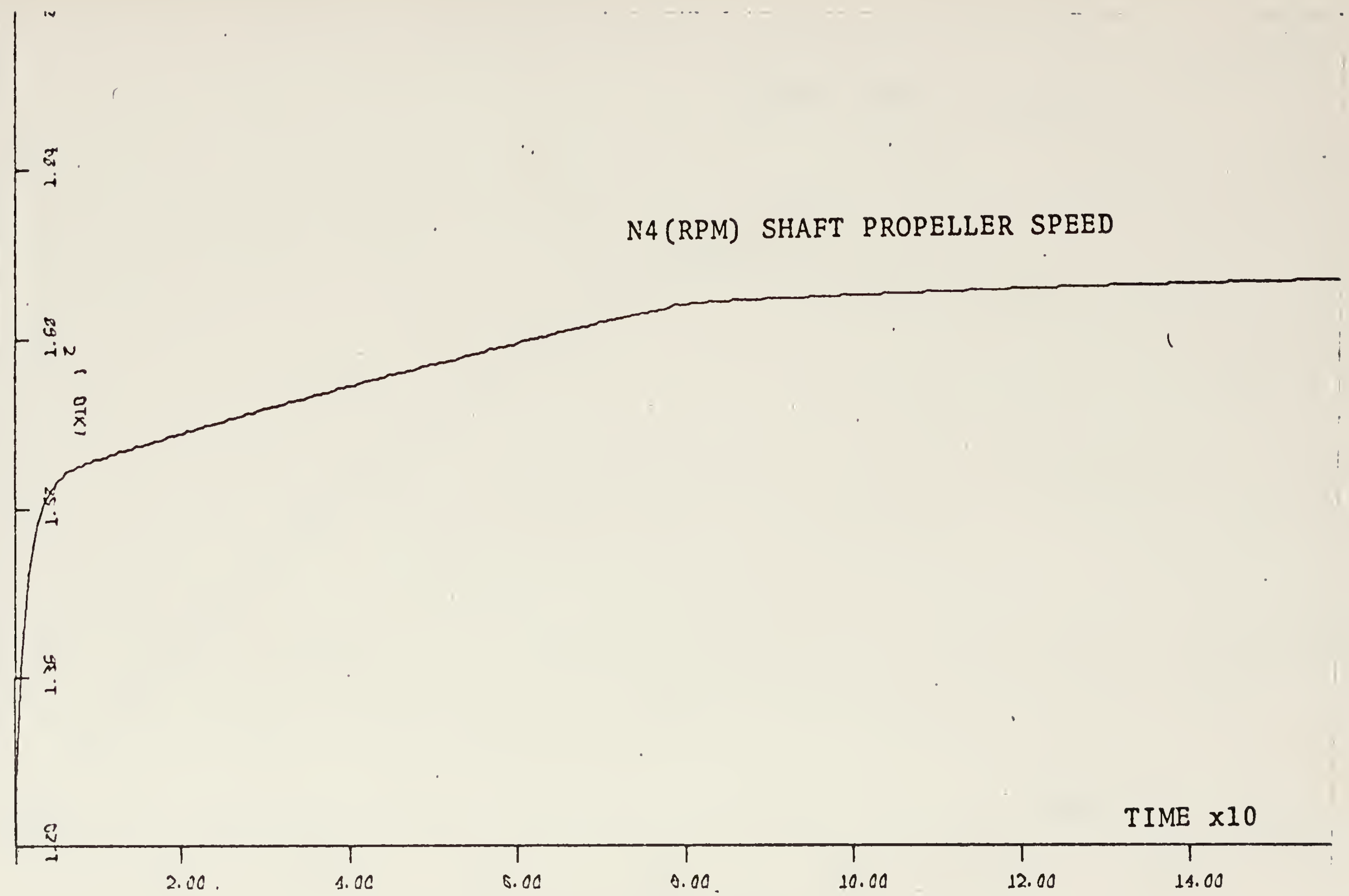



Figure B5. Shaft Propeller Speed N4 versus Time.

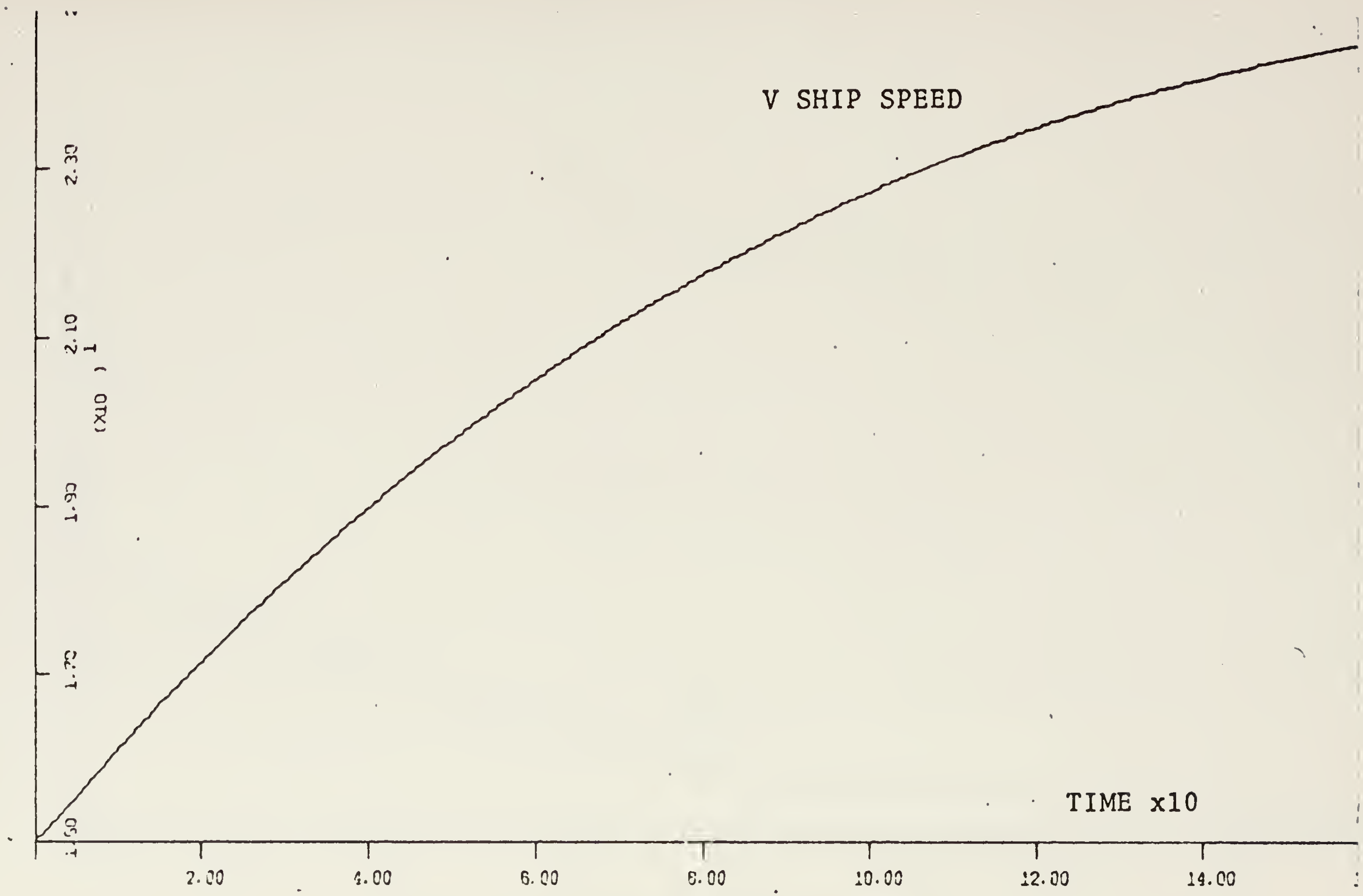



Figure B6. Ship Speed versus Time.

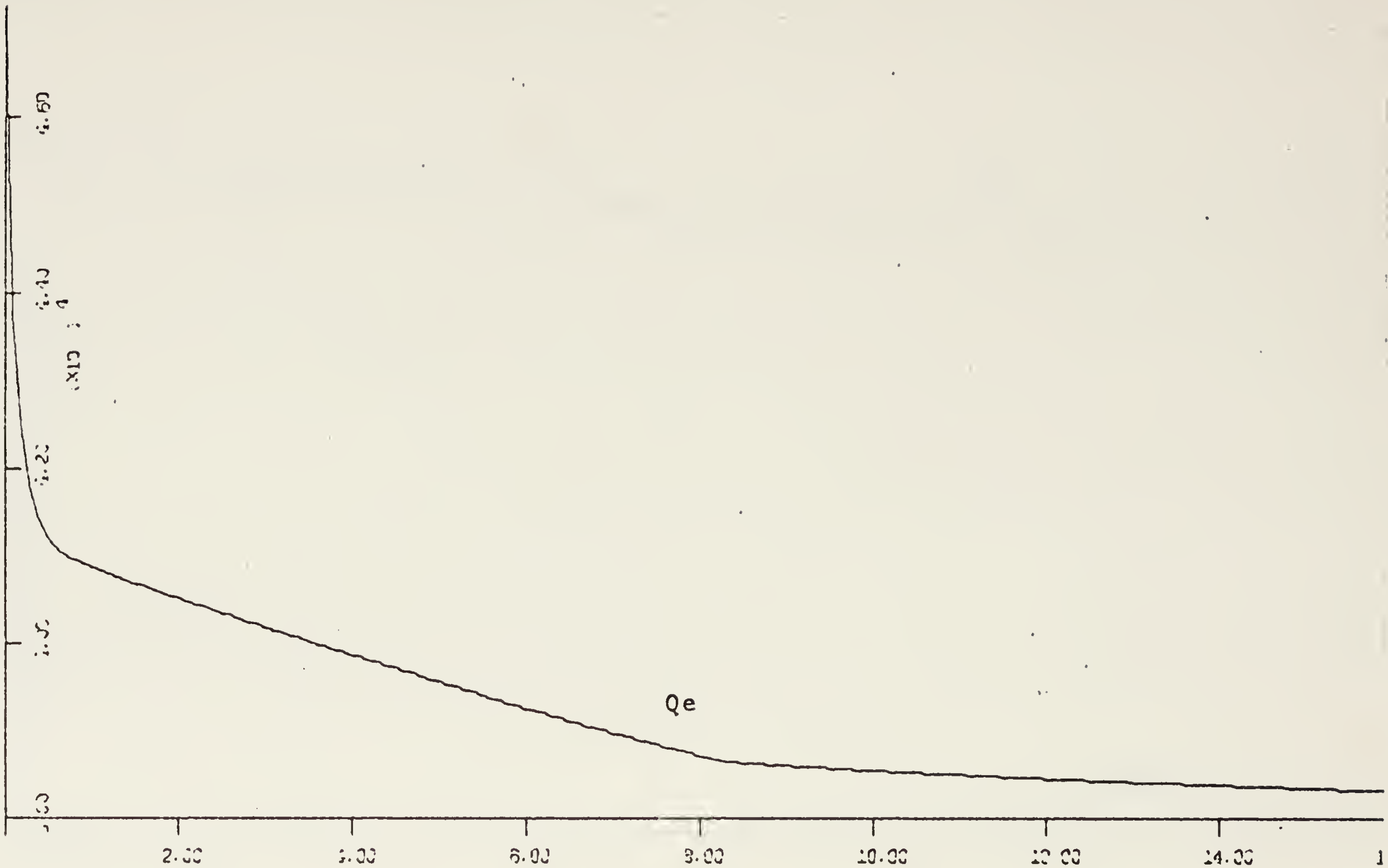



Figure B7. Shaft Torque versus Time.

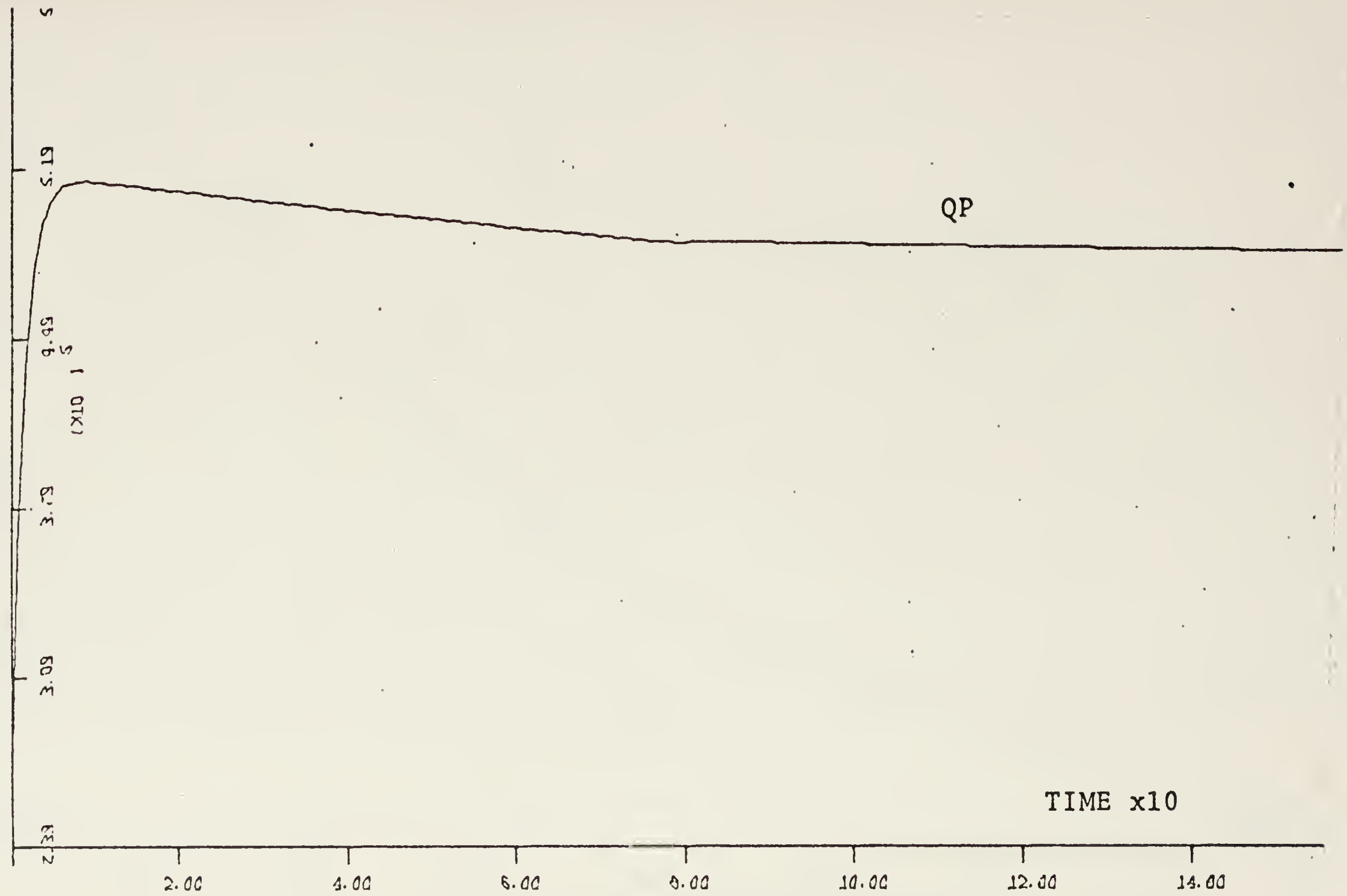



Figure B8. Propeller Reaction Torque Qp versus Time.

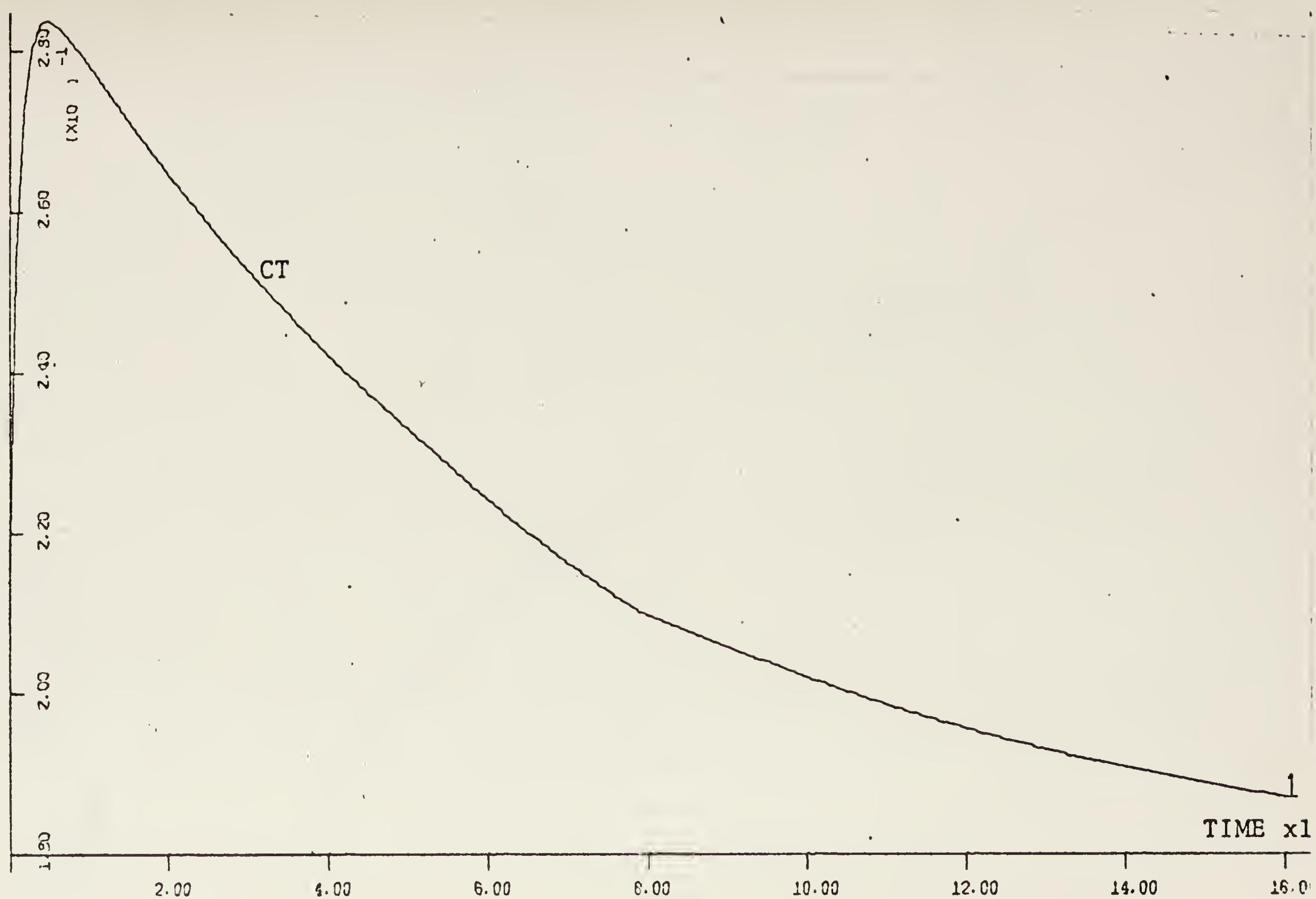



Figure B9. Thrust Coefficient Ct versus Time.

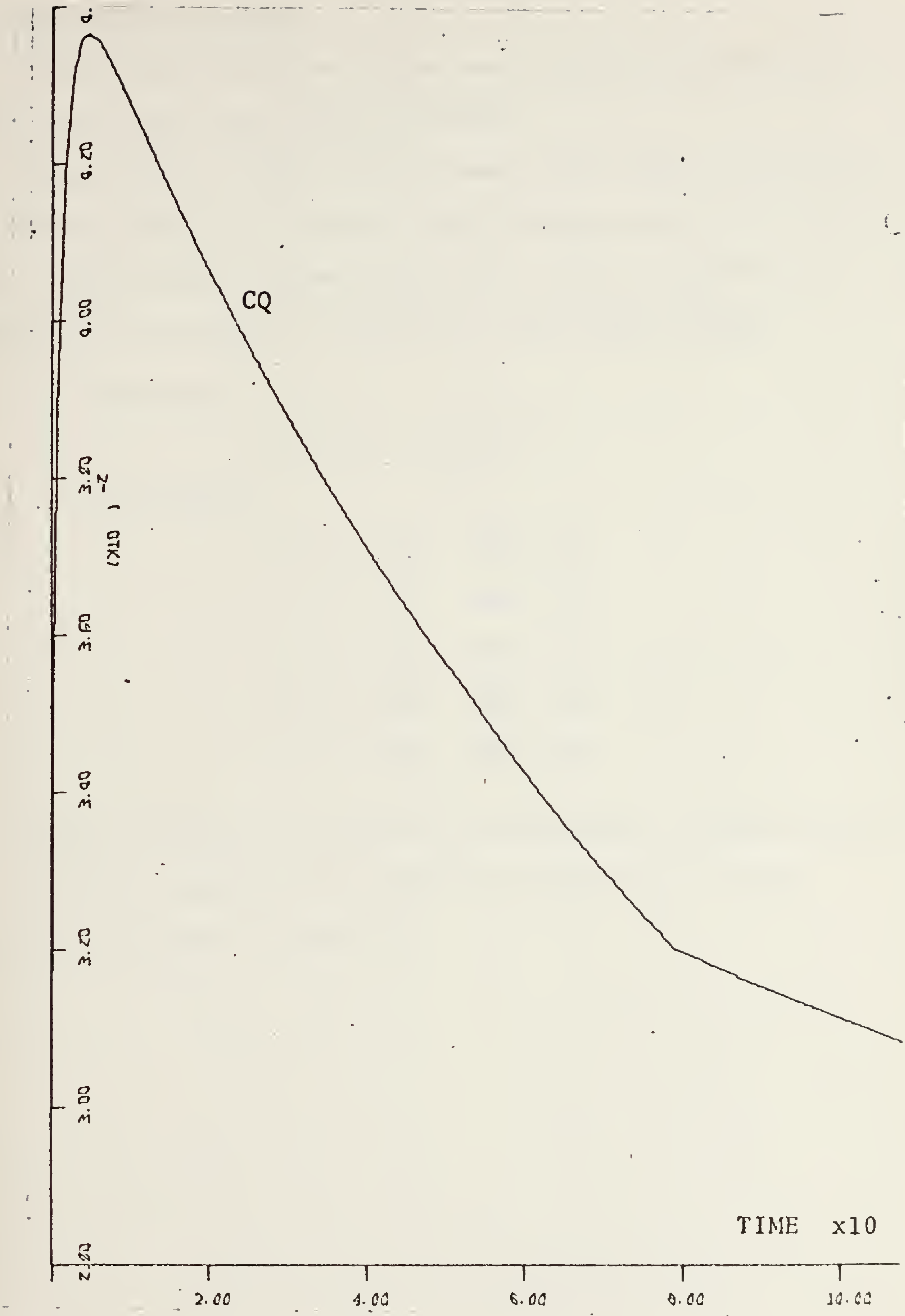



Figure B10. Torque Coefficient Cq versus Time

## B. POWER TURBINE GOVERNING:

Turbine speeds with governor are shown in Fig. A4 and compared with the responses that occur without a governor.

For small step changes in power demand at 7000 Lb/hr fuel flow rate, the governor, which has a rate of 40 Lb/hr. RPM and time lag $1/\tau=1/5=0.2$ sec., causes the power turbine response to be reduced from 80 sec. to 20 sec. with an overshoot of 3.92% of the final change in speed.

RPM command

$$n^* = 120.+\Delta.\ \mathrm{STEP}(0.)$$

Now changing

| | | |
|---|---|---|
| $\Delta$ = 45. | RPM | (Fig. C1) |
| $\Delta$ = 40. | RPM | (Fig. C2) |
| $\Delta$ = 30. | RPM | (Fig. C3) |
| $\Delta$ = 20. | RPM | (Fig. C4) |
| $\Delta$ = 10. | RPM | (Fig. C5) |

Percent Overshoot as a function of rudder angle is shown on Table 1.

The block diagram for the combined propulsion plant and hull equations were shown in Appendix B.

| Increase (rpm) | N4(MAX.) | N4(steady state) | ERROR | Percent Overshoot |
|---|---|---|---|---|
| 45 | 169.39 | 163.00 | 6.39 | 3.92 |
| 40 | 167.58 | 158.73 | 8.85 | 5.58 |
| 30 | 163.66 | 150.22 | 13.44 | 8.94 |
| 20 | 160.33 | 142.07 | 18.26 | 12.85 |
| 10 | 157.79 | 133.05 | 27.74 | 18.59 |

TABLE 1. Percent Overshoot with Governing.

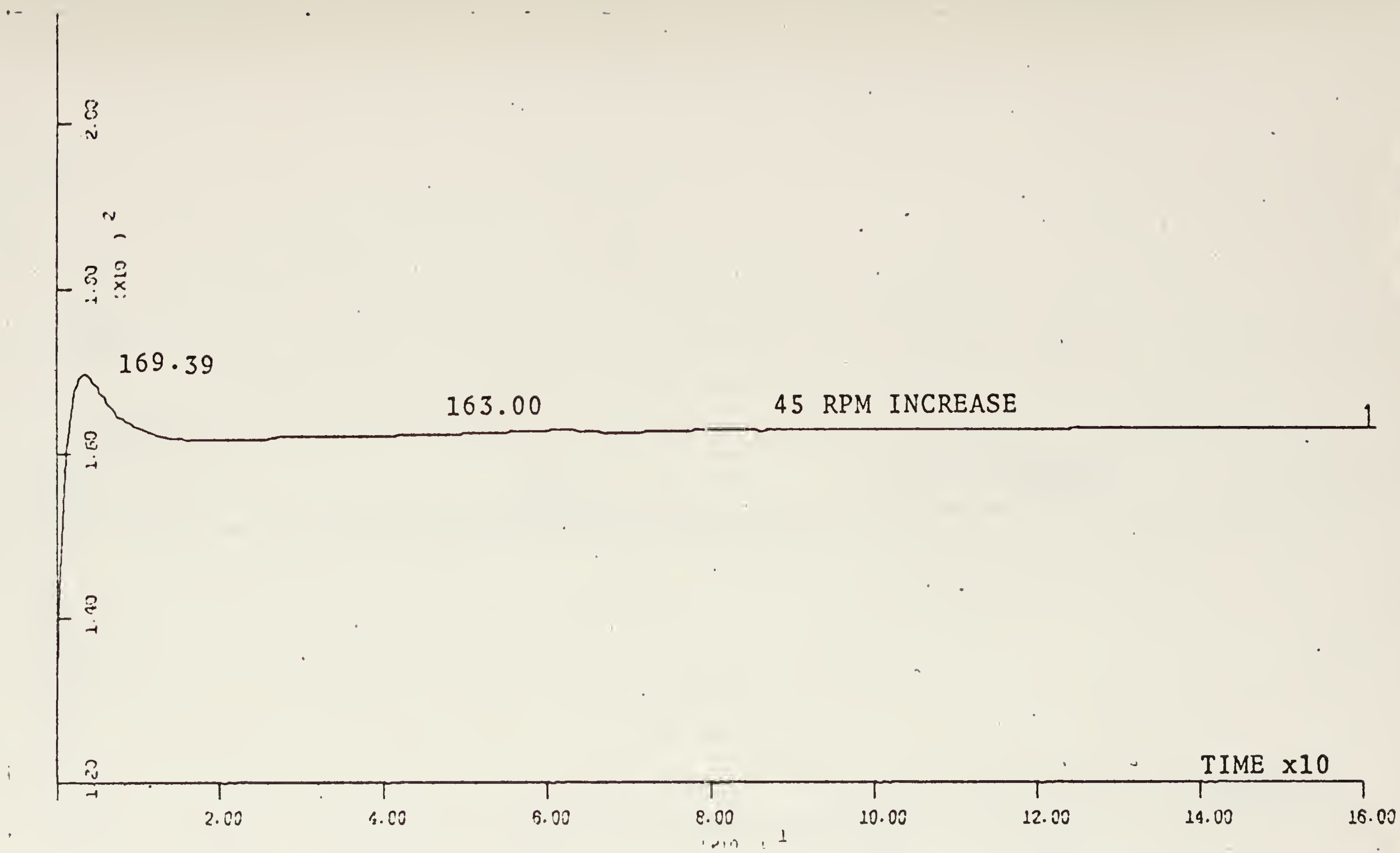



Figure C1. Shaft-Speed versus Time, with 45 RPM Increase

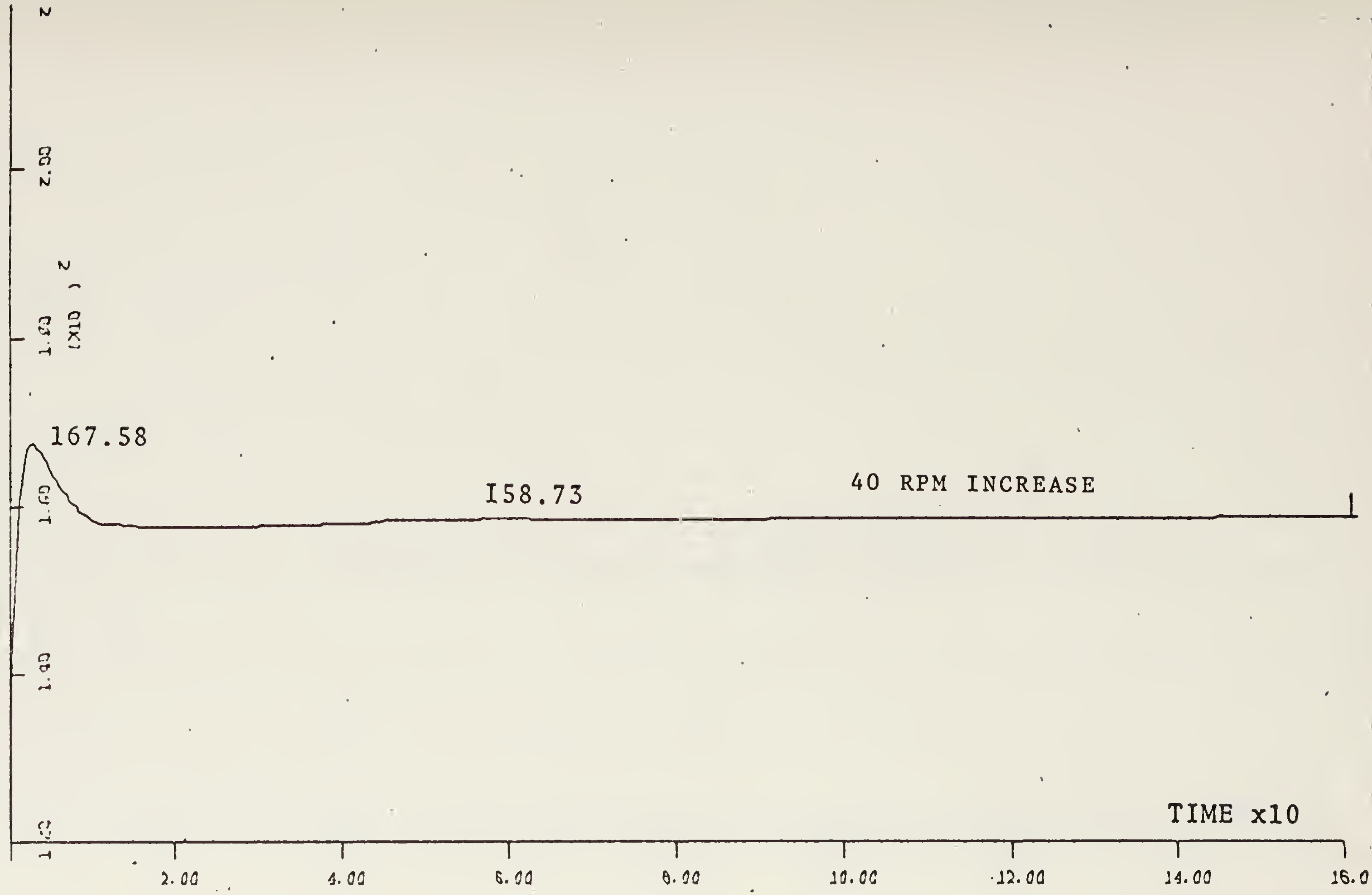



Figure C2. Shaft Speed versus Time, with 40 RPM Increase

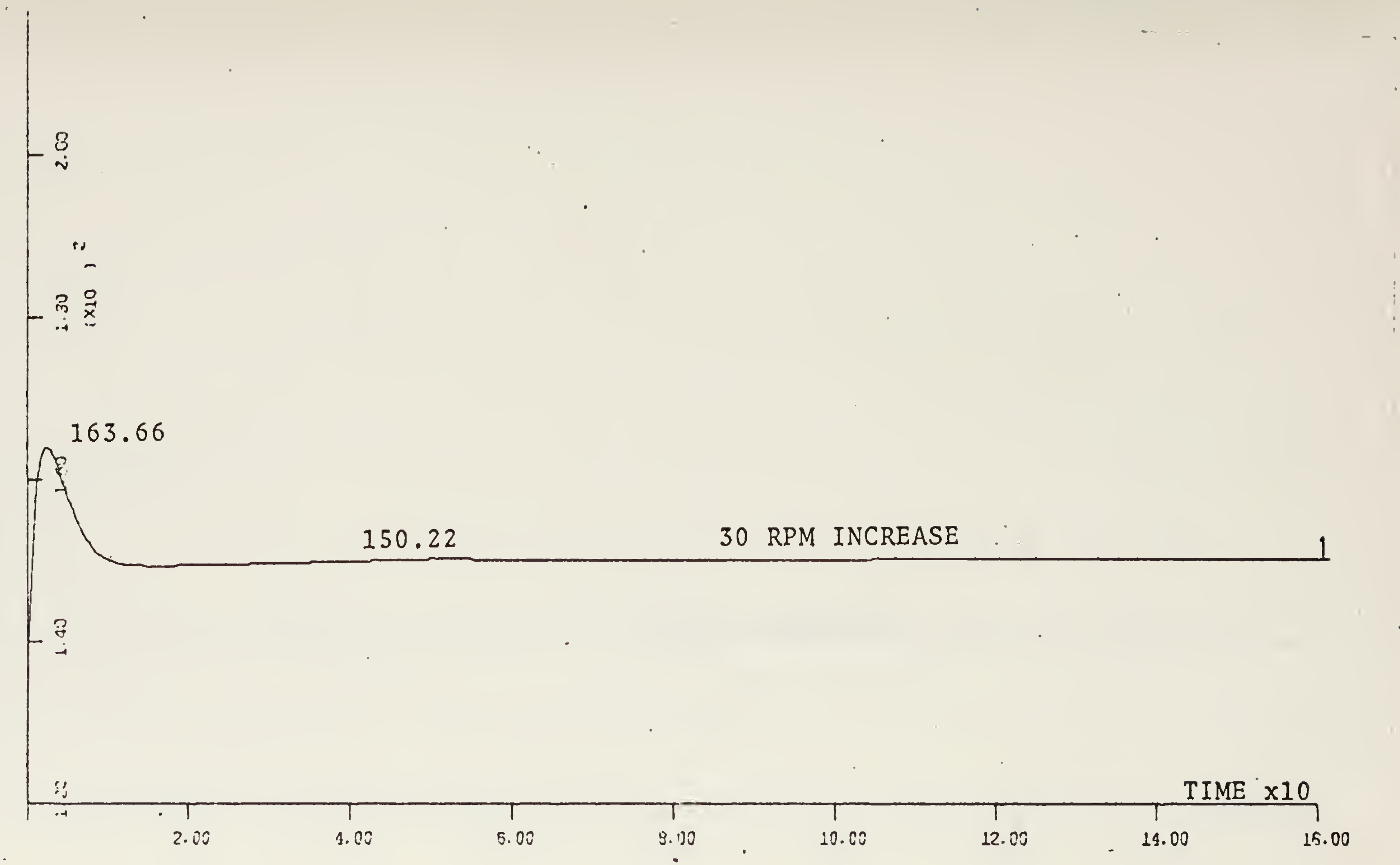



Figure C3. Shaft-Speed versus Time, with 30 RPM Increase

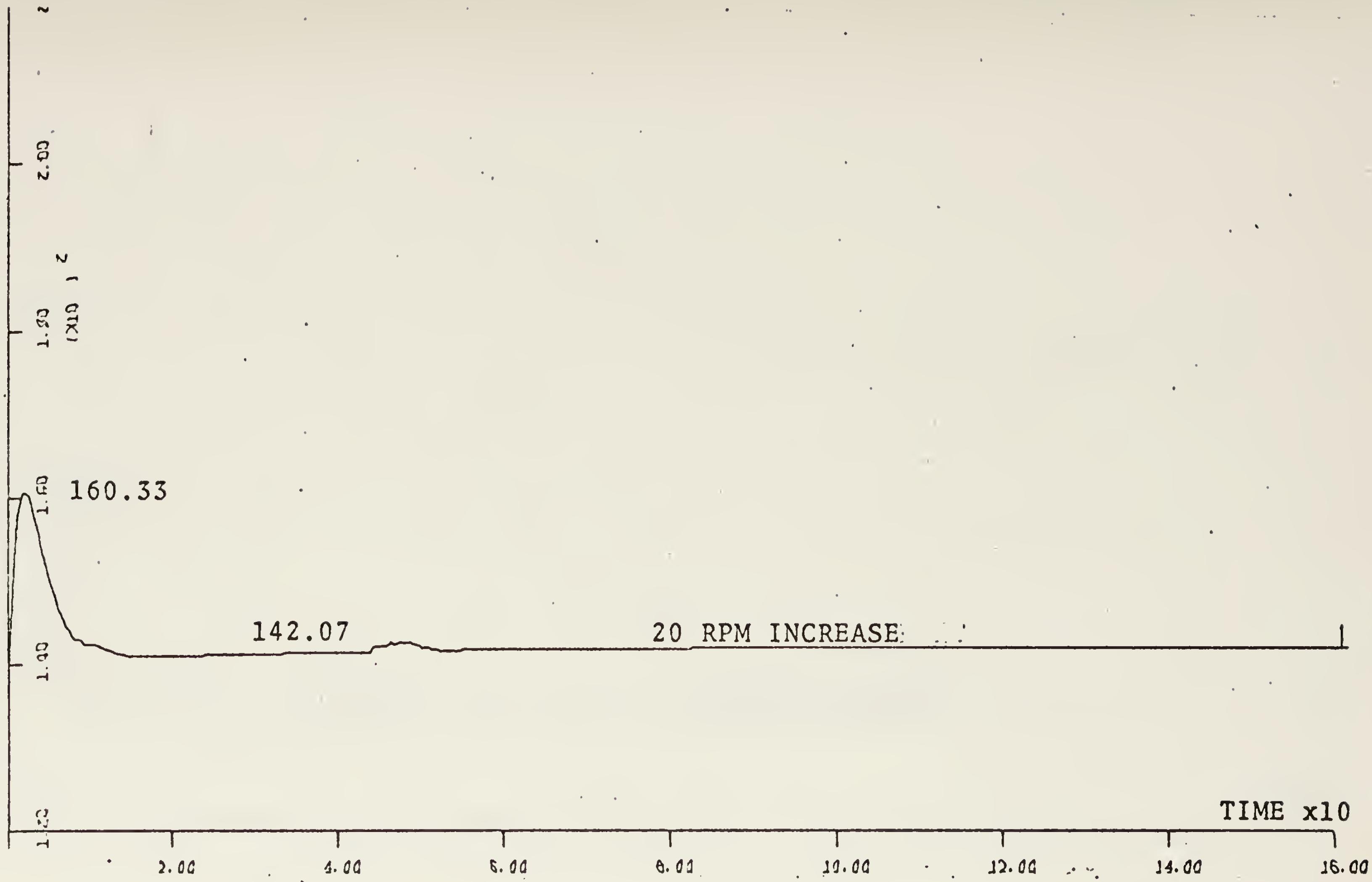



Figure C4. Shaft-Speed versus Time, with 20 RPM Increase

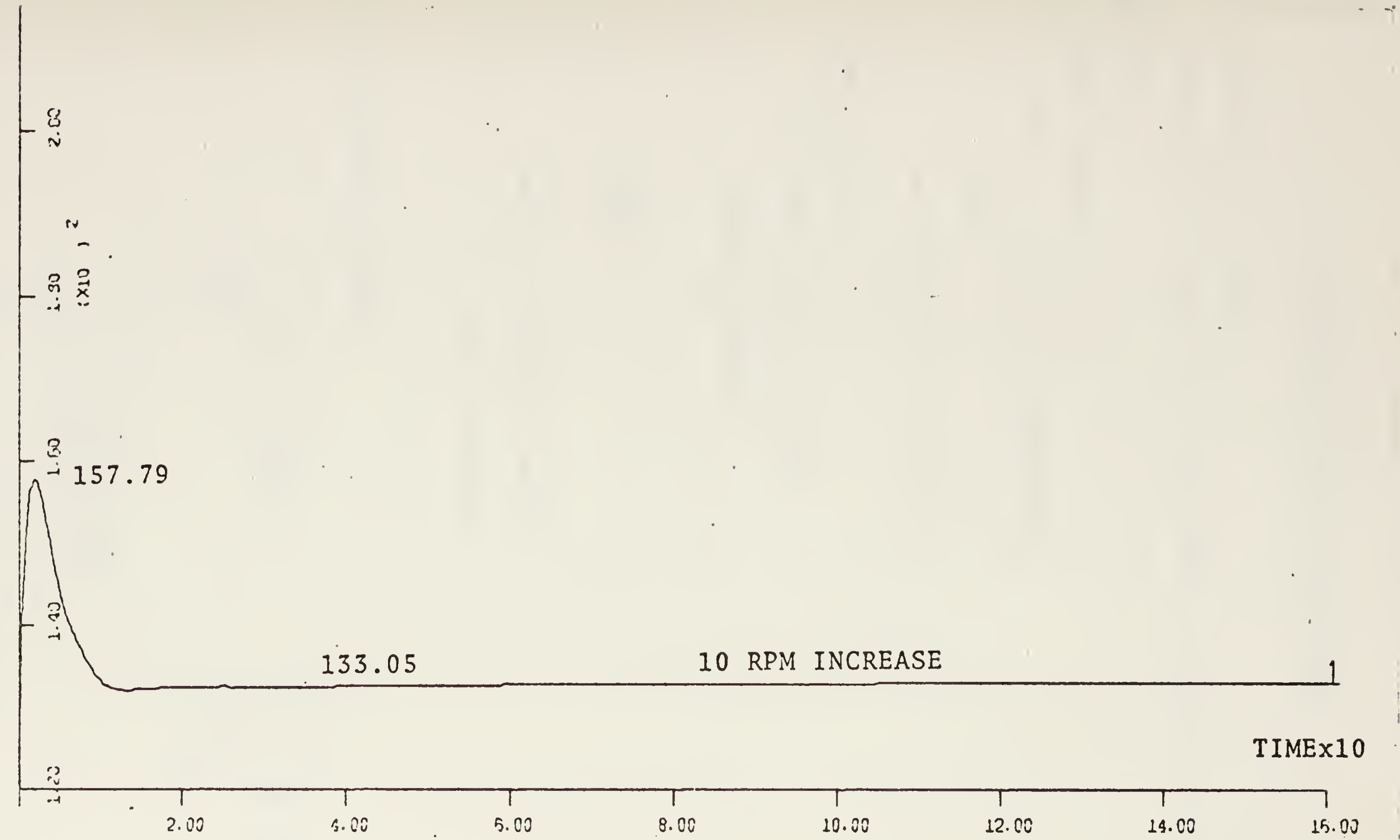



Figure C5. Shaft-Speed versus Time, with 10 RPM Increase

# V. EQUATIONS OF MOTION OF THE HULL

## A. NEWTON'S LAW OF MOTION:

Newton's Law of motion for a rigid body can be written as two equations:

FORCE EQUATION

$$\vec{F} = \text{Force on body} = d(\overrightarrow{\text{Momentum}})/dt$$

$$= d(m\vec{U}_G)$$

Where $\vec{U}_G$ Velocity of body

MOMENT EQUATION

$$\vec{M} = \text{Moment acting on a body}$$

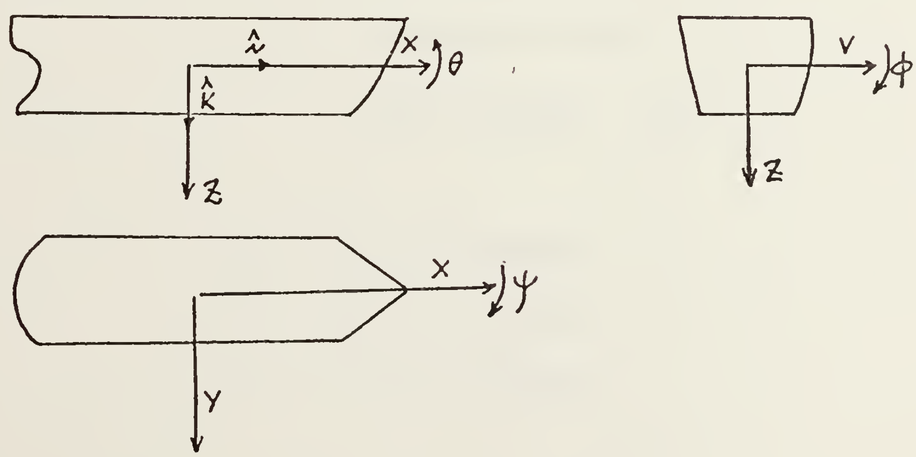
$$= \frac{d(\text{Angular momentum})}{dt}$$

$$= \frac{d(\overrightarrow{I\Omega})}{dt}$$

Where I = Moment of inertia

$\Omega$ = Angular velocity

## B. SIX DEGREES OF FREEDOM:



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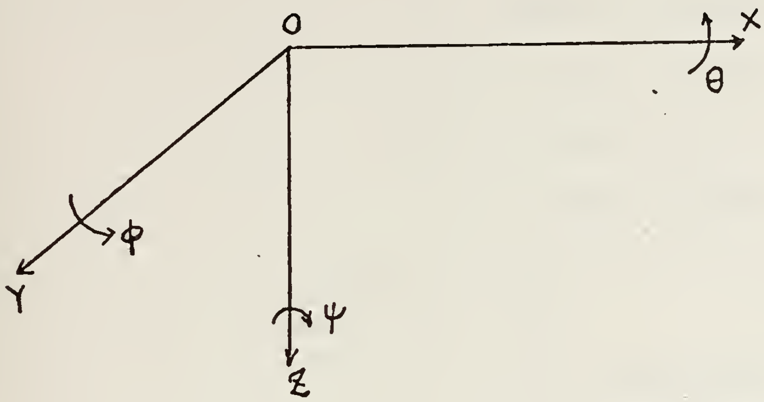



Z: Vertical axis, positive downward

Y: Tranverse axis, positive staboard

X: Longitudinal axis, positive forward

$\phi$ : Roll angle
$\theta$ : Pitch angle
$\psi$ : Yaw angle

Positive rotations are indicated in the sketch above

$$\vec{F} = \frac{d(m\vec{U})}{dt} = m\dot{\vec{U}} + X(mU)$$

$$\vec{M} = \frac{d(\vec{H})}{dt} = \dot{\vec{H}} + \vec{\Omega} \times \vec{H}$$

m: Mass of ship

$$\vec{U} = ui+vj+wk \qquad (3)$$

u: Rate of surging

v: Rate of swaying

w: Rate of heaving

$$\vec{R} = pi + qj + rk \qquad (4)$$

R: Angular velocity

$p = \dot{\phi}$ = Rate of roll

$q = \dot{\theta}$ = Rate of yaw

$r = \dot{\psi}$ = Rate of pitch

$$\vec{F} = Xi + j + Zk \qquad (5)$$

X: Hydrodynamic force along X axis

Y: Hydrodynamic force along Y axis

Z: Hydrodynamic force along Z axis

$\vec{M}$ = Moment vector acting on body

$$= Ki + Mj + Nk \qquad (6)$$

K: Rolling moment about X axis

M: Pitching moment about Y axis

N: Yawing moment about Z axis.

Substituting equations (3),(4),(5), and (6) into equation (2) gives

$$X = m(\dot{u} + qw - rv - X_G(q^2 + r^2) + Y_G(pq - \dot{r}) + Z_G(pr + \dot{q}))$$

$$Y = m(\dot{v} + ru - pw - Y_G(p^2 + r^2) + Z_G(qr - \dot{p}) + X_G(qp + \dot{r}))$$

$$Z = m(\dot{w} + pv - qu - Z_G(p^2 + q^2) + X_G(rp - \dot{q}) + Y_G(rq + \dot{p}))$$

$$K = I_X\dot{p} + (I_Z - I_Y)\ qr - m(Y_G(\dot{w} + \dot{p}v - qu) - Z_G(\dot{v} + ru - pw))$$

$$M = I_Y\dot{q} + (I_X - I_Z)\ rp - m(Z_G(\dot{u} + qw - rv) - X_G(\dot{w} + pv - qu))$$

$$N = I_Z\dot{r} + (I_Y - I_X)\ pq - m(X_G(\dot{v} + ru - pw) - Y_G(\dot{u} + qw - rv))$$

For the surface ship in calm water, roll, pitching and heaving are taken as zero. That means p=q=w=0 and most ships have $Y_G$=0.

Then equation (7) becomes:

$$X = m(\dot{u} - rv - X_G r^2)$$

$$Y = m(\dot{v} + ru + X_G r\ ) \qquad (8)$$

$$N = I_Z \dot{r} - m(X_G(\dot{v} + ur))$$

## C. LINEARIZATION OF THE EQUATIONS OF MOTION:

### 1. X Equation

The nonlinear TAYLOR expansion for the X equation is

$$\begin{aligned} X = X^o &+ \left[X_u \Delta u + X_v v + X_r r + X_\delta \delta\right] \\ &+ \frac{1}{2}\left[X_{uu}(\Delta u)^2 + X_{vv} v^2 + X_{rr} r^2 + X_{\delta\delta}\delta^2 \right. \\ &\quad \left. + 2X_{uv}\Delta u v + \cdots + 2X_{r\delta} r\delta\right] \\ &+ \frac{1}{6}\left[X_{uuu}(\Delta u)^3 + X_{vvv} v^3 + \cdots + X_{\delta\delta\delta}\delta^3 \right. \\ &\quad + 3X_{uuv}(\Delta u)^2 v + 3X_{uur}(\Delta u)^2 r + \cdots + 3X_{r\delta\delta} r\delta^2 \\ &\quad \left. + 6X_{uvr}(\Delta u) v r + \cdots\cdots\right] \end{aligned} \qquad (5)$$

Note:

1. The TAYLOR expansion of the equation above includes terms up to third order, since terms higher than third order are not significant.

2. Since X is an EVEN function of v, of , of

$$X(v) = a_2 v^2 + a_4 v^4 + a_6 v^6 + \cdots$$

$$X(r) = b_2 r^2 + b_4 r^4 + b_6 r^6 + \cdots$$

$$X(\delta) = c_2 \delta^2 + c_4 \delta^4 + c_6 \delta^6 + \cdots$$

Then the odd powers of $v, r, \delta$ are zero i.e. all $X_v v, X_r r, X_\delta \delta$ are equal zero.

Thus equation (5) becomes:

$$X = X^{o} + \frac{1}{2} X_{uu}(\Delta u)^2 + \frac{1}{2} X_{vv} v^2 + \frac{1}{2} X_{rr} r^2 + \frac{1}{2} X_{\delta\delta}\delta^2$$
$$+ X_{uv}(\Delta u) v + X_{ur}(\Delta u) r + X_{u\delta}(\Delta u)\delta + X_{vr} vr + X_{v\delta} v\delta + X_{r\delta} r\delta \quad (6)$$

Some of these terms are equal to zero (see Table 2)

then $X=X_0=0$

2. Y Equation

The nonlinear TAYLOR expansion for the Y equation is:

$$Y = Y^{o} + \left[Y_u \Delta u + Y_v v + Y_r r + Y_\delta \delta\right]$$
$$+ \frac{1}{2}\left[Y_{uu}(\Delta u)^2 + Y_{vv} v^2 + Y_{rr} r^2 + Y_{\delta\delta}\delta^2 + 2Y_{ur}\Delta u \cdot r + \dots\right.$$
$$\left. + 2 Y_{r\delta} r\delta\right] +$$
$$+ \frac{1}{6}\left[Y_{uuu}(\Delta u)^3 + Y_{vvv} v^3 + Y_{rrr} r^3 + Y_{\delta\delta\delta}\delta^3\right.$$
$$+ 3 Y_{uuv}(\Delta u)^2 v + 3 Y_{uur}(\Delta u)^2 r + \dots + 3 Y_{r\delta\delta} r\delta^2$$
$$\left. + 6 Y_{urv} \Delta u r v + \dots \dots \right] \quad (7)$$

NOTE:

1. The terms higher than third order are not significant.
2. Y is an odd function of v,r,$\delta$

$$Y(v) = d_1 v + d_3 v^3 + d_5 v^5 + \dots$$
$$Y(r) = e_1 r + e_3 r^3 + e_5 r^5 + \dots$$
$$Y(\ ) = f_1 \delta + f_3 \delta^3 + f_5 \delta^5 + \dots$$

Then equation (7) becomes:

$$Y = Y^{o} + Y_u \Delta u + Y_v v + Y_r r + Y_\delta \delta +$$
$$+ \frac{1}{6} Y_{uuu} (\Delta u)^3 + \frac{1}{6} Y_{vvv} v^3 + \frac{1}{6} Y_{rrr} r^3 + \frac{1}{6} Y_{\delta\delta\delta} \delta^3$$
$$+ \frac{1}{2} Y_{uuv} (\Delta u)^2 v + \frac{1}{2} Y_{uur} (\Delta u)^2 r + \frac{1}{2} Y_{uu\delta} (\Delta u)^2 \delta + \frac{1}{2} Y_{rvv} r v^2 + \frac{1}{2} Y_{\delta rr} \delta r^2$$
$$+ \frac{1}{2} Y_{v\delta\delta} v \delta^2 + \frac{1}{2} Y_{r\delta\delta} r \delta^2 + Y_{vr\delta} v r \delta$$

Where the indicated terms are equal to zero (see Table 3)

$$Y = Y_o + Y_v v + Y_r r + Y_\delta \delta + \frac{1}{6} Y_{vvv} v^3 + \frac{1}{6} Y_{\delta\delta\delta} \delta^3 + \frac{1}{2} Y_{rvv} r v^2 + \frac{1}{6} Y_{rrr} r^3 \tag{8}$$

3. <u>N Equation</u>

The nonlinear TAYLOR expansion for the N equation is:

$$N = N^{o} + N_u \Delta u + N_v v + N_r r + N_\delta \delta +$$
$$+ \frac{1}{2} \Big[ N_{uu} (\Delta u)^2 + N_{vv} v^2 + N_{rr} r^2 + N_{\delta\delta} \delta^2 +$$
$$+ 2 N_{ur} (\Delta u) r + \dots + 2 N_{r\delta} r \delta \Big]$$
$$+ \frac{1}{6} \Big[ N_{uuu} \Delta u^3 + N_{vvv} v^3 + N_{rrr} r^3 + N_{\delta\delta\delta} \delta^3$$
$$+ 3 N_{uuv} (\Delta u)^2 v + 3 N_{uur} (\Delta u)^2 r + \dots + 3 N_{r\delta\delta} r \delta^2$$
$$+ 6 N_{uvr} \Delta u . v r + \dots \tag{9}$$

NOTE:

1. The terms higher than third order are not significant.

2. N is an odd function of v, r, $\delta$

$$N(v) = g_1 v + g_3 v^3 + g_5 v^5 + \dots$$
$$N(r) = h_1 r + h_3 r^3 + h_5 r^5 + \dots$$
$$N(\delta) = K_1 \delta + K_3 \delta^3 + K_5 \delta^5 + \dots$$

Then equation (9) becomes:

$$N = N_u \Delta u + N_v v + N_r r + N_\delta \delta + \frac{1}{6} N_{uuu} (\Delta u)^3 + \frac{1}{6} N_{vvv} v^3 + \frac{1}{6} N_{rrr} r^3 + \frac{1}{6} N_{\delta\delta\delta} \delta^3 + \frac{1}{2} N_{uuv} (\Delta u)^2 v + \frac{1}{2} N_{uur} \Delta u^2 r + \cdots + N_{vr\delta} v r \delta$$

The indicated terms are equal to zero (see Table 4)

Then

$$N = N_v v + N_r r + N_\delta \delta + \frac{1}{6} N_{vvv} v^3 + \frac{1}{6} N_{rrr} r^3 + \frac{1}{2} N_{vrr} v r^2 + \frac{1}{2} N_{rvv} r v^2 \tag{10}$$

Combining the third order TAYLOR expansion for X,Y, and N with the dynamic response terms of the X,y, and N equation.

X equation $X = 0$

Y equation

$$(m - Y_{\dot{v}})\dot{v} + (mX_G - Y_{\dot{r}})\dot{r} = Y(u,v,r,\delta)$$

N equation (1)

$$(mX_G - N_{\dot{v}})\dot{v} + (I_Z - N_{\dot{r}})\dot{r} = N(u,v,r,\delta)$$

Using CRAMER'S rule to solve these equations

$$\dot{v} = \frac{\begin{vmatrix} Y(u,v,r,\delta) & mX_G - Y_r \\ N(u,v,r,\delta) & I_Z - N_r \end{vmatrix}}{\begin{vmatrix} m - Y_{\dot{v}} & mX_G - Y_{\dot{r}} \\ mX_G - N_{\dot{v}} & I_Z - N_{\dot{r}} \end{vmatrix}}$$

$$\dot{r} = \frac{\begin{vmatrix} m - Y_{\dot{v}} & Y(u,v,r,\ ) \\ mX_G - N_{\dot{v}} & N(u,v,r,\ ) \end{vmatrix}}{\begin{vmatrix} m - Y_{\dot{v}} & mX_G - Y_{\dot{r}} \\ mX_G - N_{\dot{v}} & I_Z - N_{\dot{r}} \end{vmatrix}}$$

TABLE 2. ASSESSMENT OF THE COEFFICIENTS IN THE X EQUATION

| Variable | Coefficient | Series 60/Model 5.1.1 | |
|---|---|---|---|
| $\dot{u}$ | $m-X\dot{u}$ | 0.1750 | |
| $\Delta u$ | Xu | ——— | |
| $\Delta u^2$ | 1/2 Xuu | ——— | |
| $\Delta u^3$ | 1/6 Xuuu | ——— | |
| $v^2$ | 1/2 Xvv | ——— | |
| $r^2$ | 1/2 Xrr + $mX_G$ | ——— | |
| $\delta^2$ | 1/2 Xδδ | ——— | |
| $v^2\Delta u$ | 1/2 Xvvu | ——— | |
| $r^2\Delta u$ | 1/2 Xrru | ——— | |
| $\delta^2\Delta u$ | 1/2 Xδδu | ——— | |
| vr | Xvr+m | ——— | |
| vδ | Xvδ | ——— | |
| rδ | Xrδ | ——— | |
| vrΔu | Xvru | ——— | |
| vδΔu | Xv u | ——— | |
| rδΔu | Xr u | ——— | |
| —— | Xo | ——— | |

Note: No entry in these columns means the coefficient was ignored.

*From PRINCIPLES OF NAVAL ARCHITECTURE, SNAME, 1968, page 548.

TABLE 3. ASSEMSSEMNT OF THE COEFFICIENTS IN THE Y EQUATION

| Variable | coefficient | Series 60/5.1. | |
|---|---|---|---|
| $\dot{v}$ | $m-Y\dot{v}$ | 0.309 | Y9 |
| $\dot{r}$ | $mX_G-Y\dot{r}$ | ——— | Y8 |
| v | Yv | -0.260 | Y1 |
| $v^3$ | 1/6 Yvvv | -2.150 | Y2 |
| $vr^2$ | 1/2 Yvrr | -1.180 | Y3 |
| $v\delta^2$ | 1/2 Yvδδ | ——— | |
| vΔu | Yvu | ——— | |
| $v\Delta u^2$ | 1/2Yvuu | ——— | |
| r | (Yr-m) | -0.0781 | YY4 |
| $r^3$ | 1/6 Yrrr | -0.0461 | Y5 |
| $rv^2$ | 1/2 Yrvv | -0.0994 | Y6 |
| $r\delta^2$ | 1/2 Yrδδ | ——— | |
| rΔu | Yru | ——— | |
| $r\Delta u^2$ | Yruu | ——— | |
| δ | 1/6 Yδ | 0.050 | Y7 |
| $\delta v^2$ | 1/2 Yδrr | ——— | |
| δΔu | Yδu | ——— | |
| $\delta\Delta u^2$ | 1/2 Yδuu | ——— | |
| vrδ | Yvrδ | ——— | |
| ——— | Yo | 0.00016 | Yo |
| Δu | $YY^o_u$ | ——— | |
| $(\Delta u)^2$ | $Y^o_{uu}$ | ——— | |

*No entry in these columns means the coefficient was ignored.

*From PRINCIPLES OF NAVAL ARCHITECTURE, SNAME, 1968, page 548.

TABLE 4. ASSESSMENT OF THE COEFFICIENT IN THE N EQUATION.

| Variable | coefficient | Series 60/Model 5.1.1 | |
|---|---|---|---|
| $\dot{v}$ | $mX_G - N\dot{v}$ | ——— | N9 |
| $\dot{r}$ | $I_Z - N\dot{r}$ | 0.0202 | N8 |
| $v$ | $Nv$ | -0.0750 | N1 |
| $v^3$ | 1/6 $Nvvv$ | -0.3850 | N2 |
| $vr^2$ | 1/2 $Nvrr$ | -0.3060 | N3 |
| $v\delta^2$ | 1/2 $Nv\delta\delta$ | ——— | |
| $v\Delta u$ | $Nvu$ | ——— | |
| $v\Delta u^2$ | 1/2 $Nvuu$ | ——— | |
| $r$ | $(Nr - mX_G)$ | -0.0569 | NN4 |
| $r^3$ | 1/6 $Nrrr$ | -0.1010 | N5 |
| $rv^2$ | 1/2 $Nrvv$ | -1.4200 | N6 |
| $r\delta^2$ | 1/2 $Nr\delta\delta$ | ——— | |
| $r\Delta u$ | $Nru$ | ——— | |
| $r\Delta u^2$ | 1/2 $Nruu$ | ——— | |
| $\delta$ | $N\delta$ | -0.0240 | N7 |
| $\delta^3$ | 1/6 $N\delta\delta\delta$ | ——— | |
| $\delta v^2$ | 1/2 $N\delta vv$ | ——— | |
| $\delta r^2$ | 1/2 $N\delta rr$ | ——— | |
| $\delta\Delta u$ | $N\delta u$ | ——— | |
| $\delta\Delta u^2$ | 1/2 $N\delta uu$ | ——— | |
| $vr\delta$ | $Nvr\delta$ | ——— | |
| — | $No$ | -0.0003 | No |
| $\Delta u$ | $N^o_u$ | ——— | |
| $(\Delta u)^2$ | $N^o_{uu}$ | ——— | |

*No entry in these columns means the coefficient was ignored.

*From PRINCIPLES OF NAVAL ARCHITECTURE, SNAME, 1968, page 549.

## D. RELATIONS BETWEEN FIXED AXES AND MOVING AXES:

So far the reference axes X,Y, and Z are fixed to the moving ship. In order to determine the path of the ship, it is convenient to take the fixed axes to the earth $X_0, Y_0$.

In figure D1., the ship is at the position A.

The YAW ANGLE $\psi$ is the angle between the U axis and the tangent line with the path at point A.

Then the following relationships between the fixed and the moving axes can be written:

$$X_0(t) = U(t)\ \text{Cos}\,\psi(t) - V(t)\text{Sin}\,\psi(t)$$

$$Y_0(t) = U(t)\ \text{Sin}\,\psi(t) + V(t)\text{Cos}\,\psi(t)$$

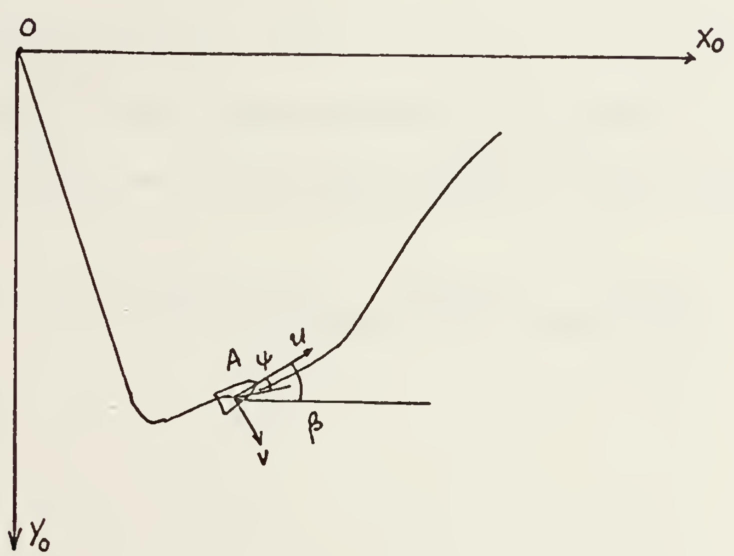



Figure D1. Relations Between Fixed Axes in the Earth and the Ship Axes.

E. RUDDER DEFLECTION:

Let $\delta$ = Rudder angle

DRATE = Rudder deflection rate.

TDMAX = Time at maximum rudder deflection

Then the rudder deflection in turning maneuver can be shown in Figure D2:

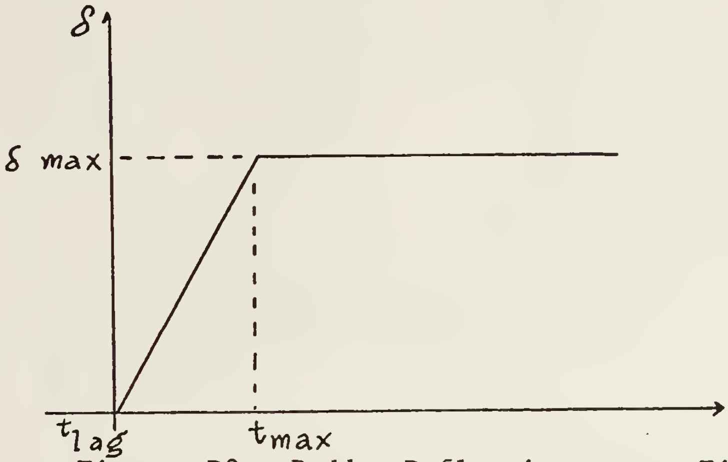



Figure D2. Rudder Deflection versus Time.

Let Rudder deflection = $\delta$

DRATE = Rudder deflection rate = $D_{max}$/TDMAX

Then the function of the rudder deflection can be written:

$$\delta = \text{DRATE}\left[\text{RAMP}(t_{lag})-\text{RAMP}(t-t_{max})\right]\frac{1}{57.3}$$

F. THE TURNING PATH OF A SHIP:

There are 4 phases of a turn:

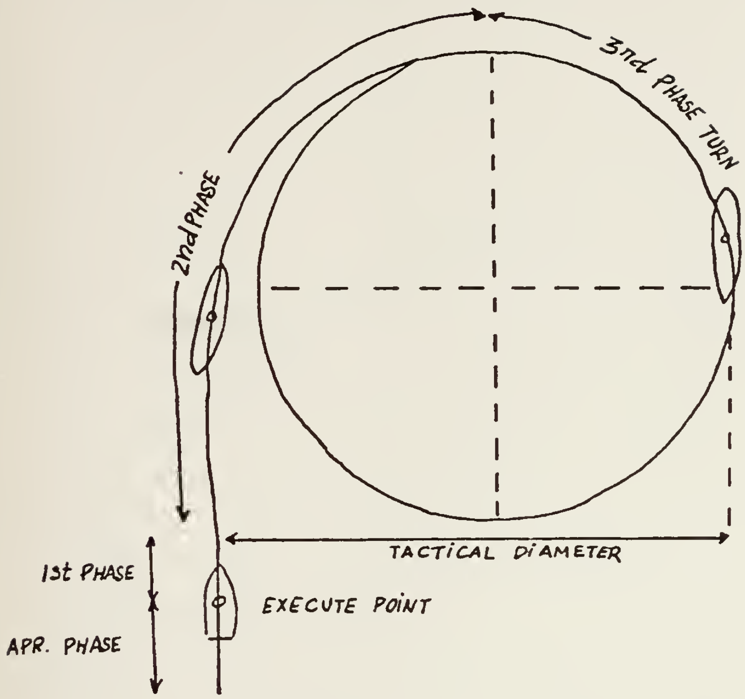



Figure D3. The Turning Path of a Ship.

| | |
|---|---|
| Approach phase | $\dot{V} = 0,\ \dot{r} = 0,\ v = 0,\ r = 0$ |
| First phase of turn | $\dot{v} \neq 0,\ \dot{r} \neq 0,\ v = 0,\ r = 0$ |
| Second phase of turn | $\dot{v} \neq 0,\ \dot{r} \neq 0,\ v \neq 0,\ r \neq 0$ |
| Third phase of turn | $\dot{v} = 0,\ \dot{r} = 0,\ v \neq 0,\ r \neq 0$ |

Using dimentional equation (1) and introducing the rudder deflection $30^{o}$. The characteristics of transient phases of a turn are shown in Figures D6, D7, D8, and D9.

| | |
|---|---|
| A–B Second phase | $v \neq 0,\ \dot{v} \neq 0,\ r \neq 0,\ \dot{r} \neq 0$ |
| B–C Third phase | $v \neq 0,\ \dot{v} = 0,\ r \neq 0,\ \dot{r} \neq 0$ |

Now using different rudder deflections $=35^{o}, 30^{o}$ the turning path of a ship is shown in Figures D4 and D5. When using the bigger deflection the steady turning radius is smaller.

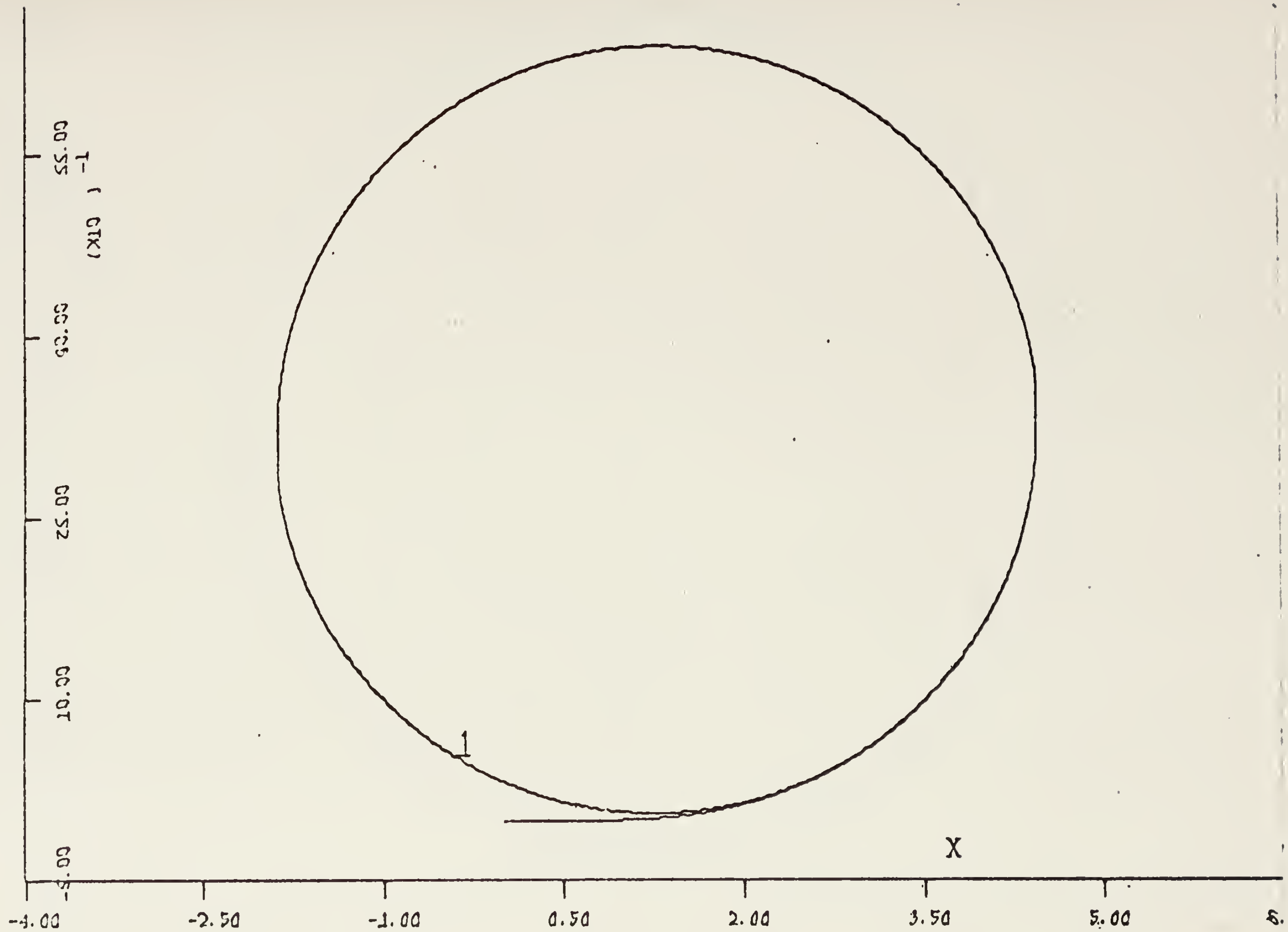



Figure D4. The Turning Path of a Ship with 35 Degree Rudder Angle.

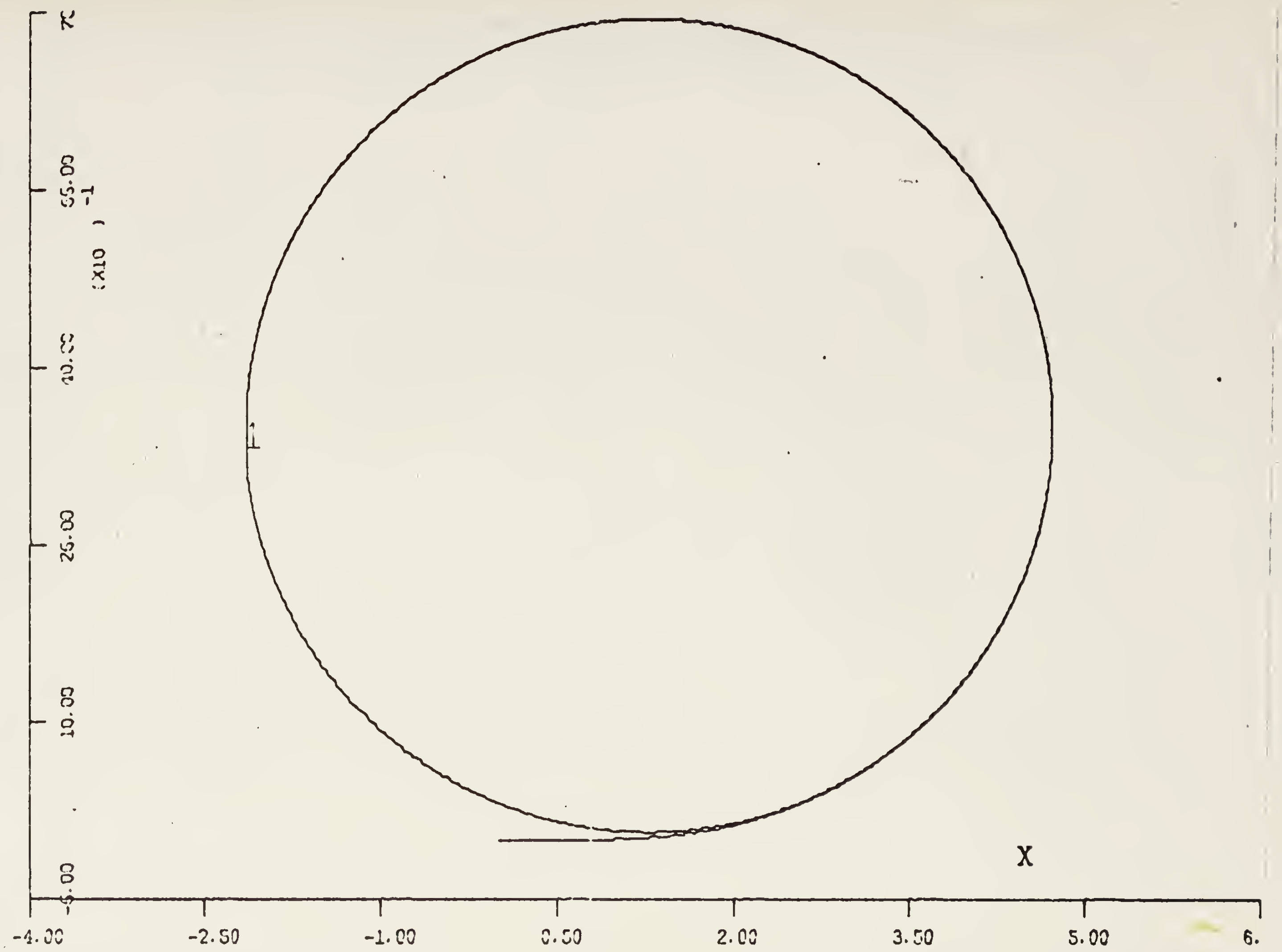



Figure D5. The Turning Path of a Ship with 30 Degree Rudder Angle.

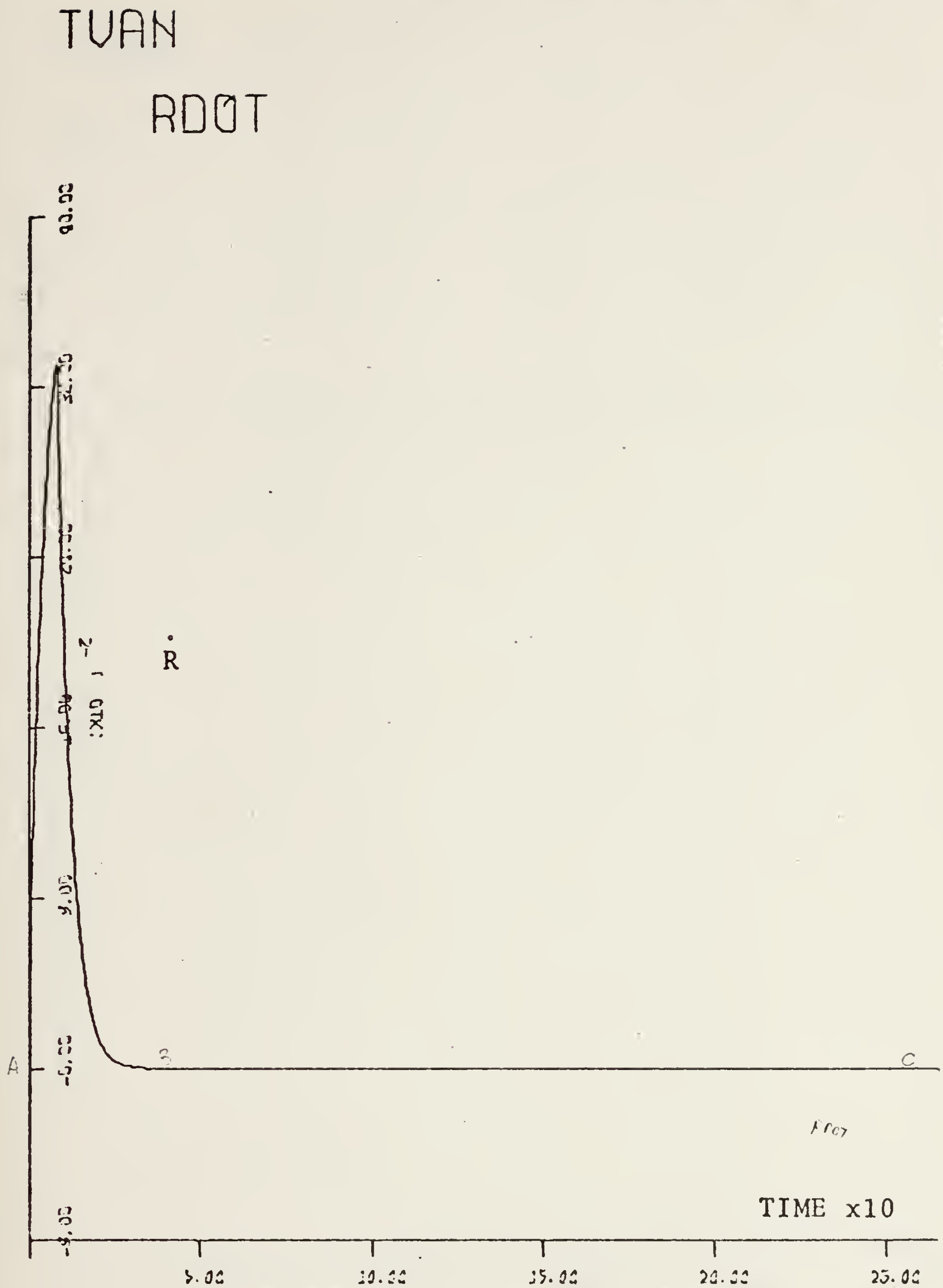



Figure D6. Angular Acceleration about Z Axis.

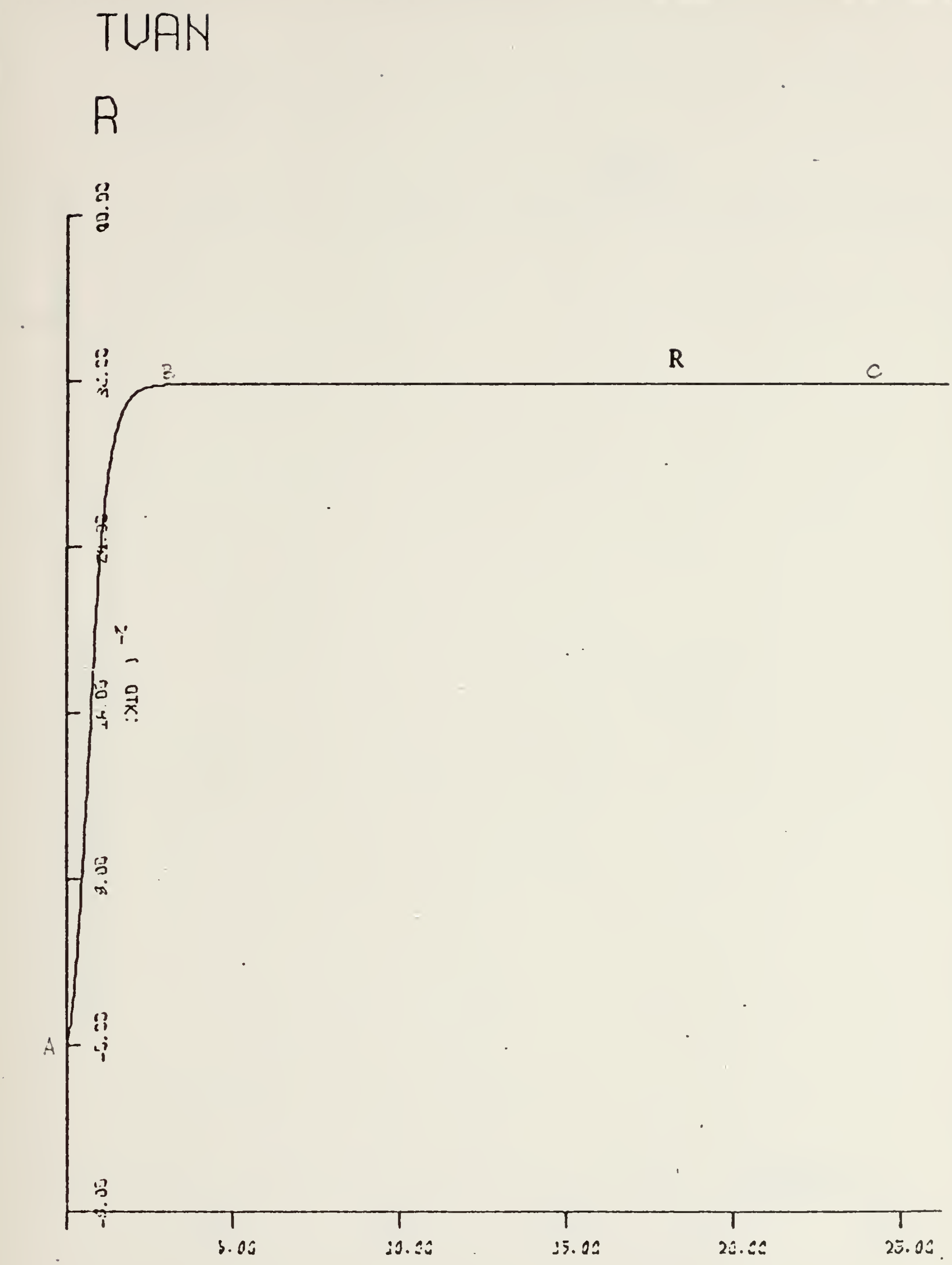



Figure D7. Angular Velocity about Z Axis.

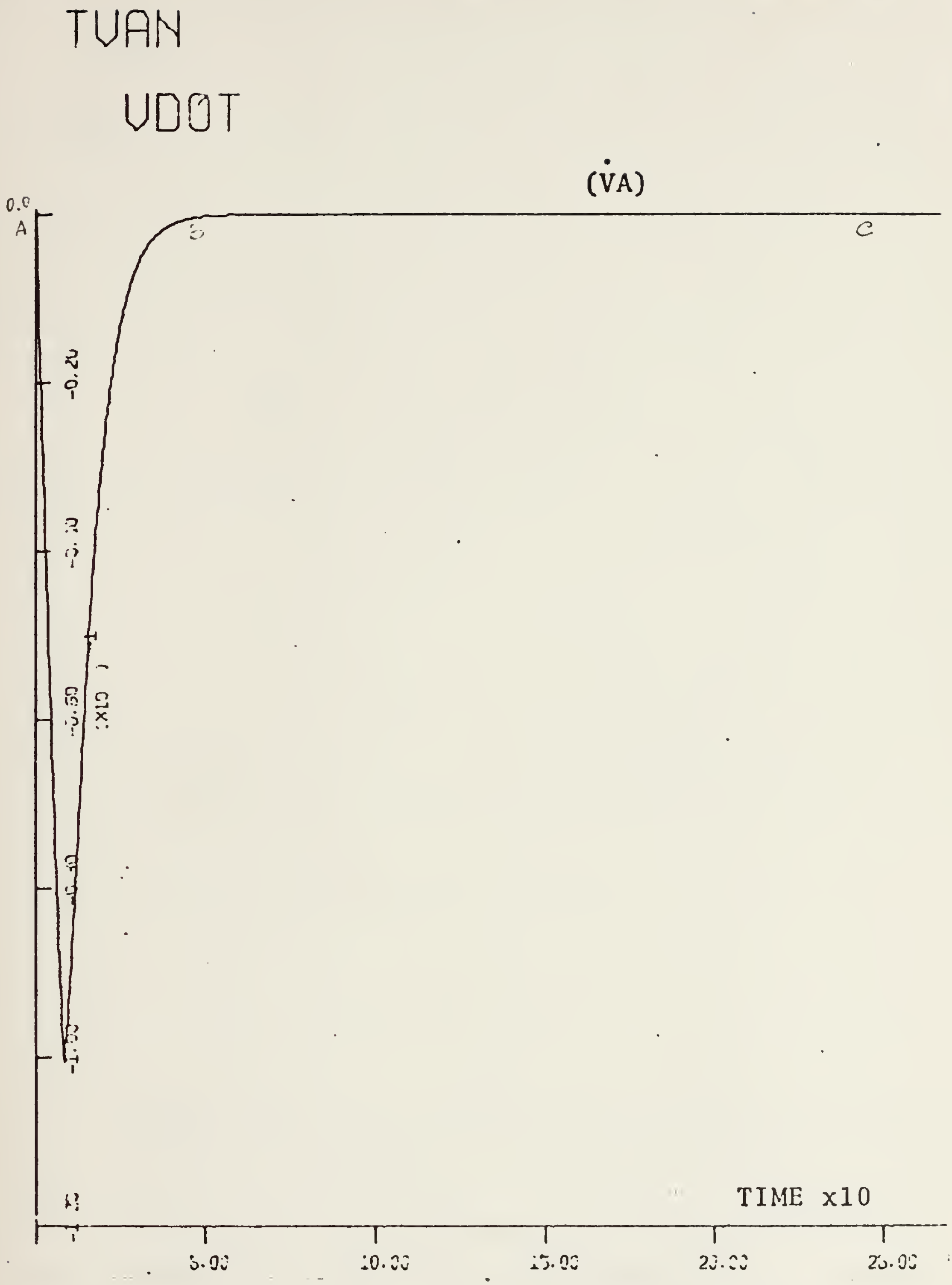



Figure D8. Angular Acceleration about Y Axis.

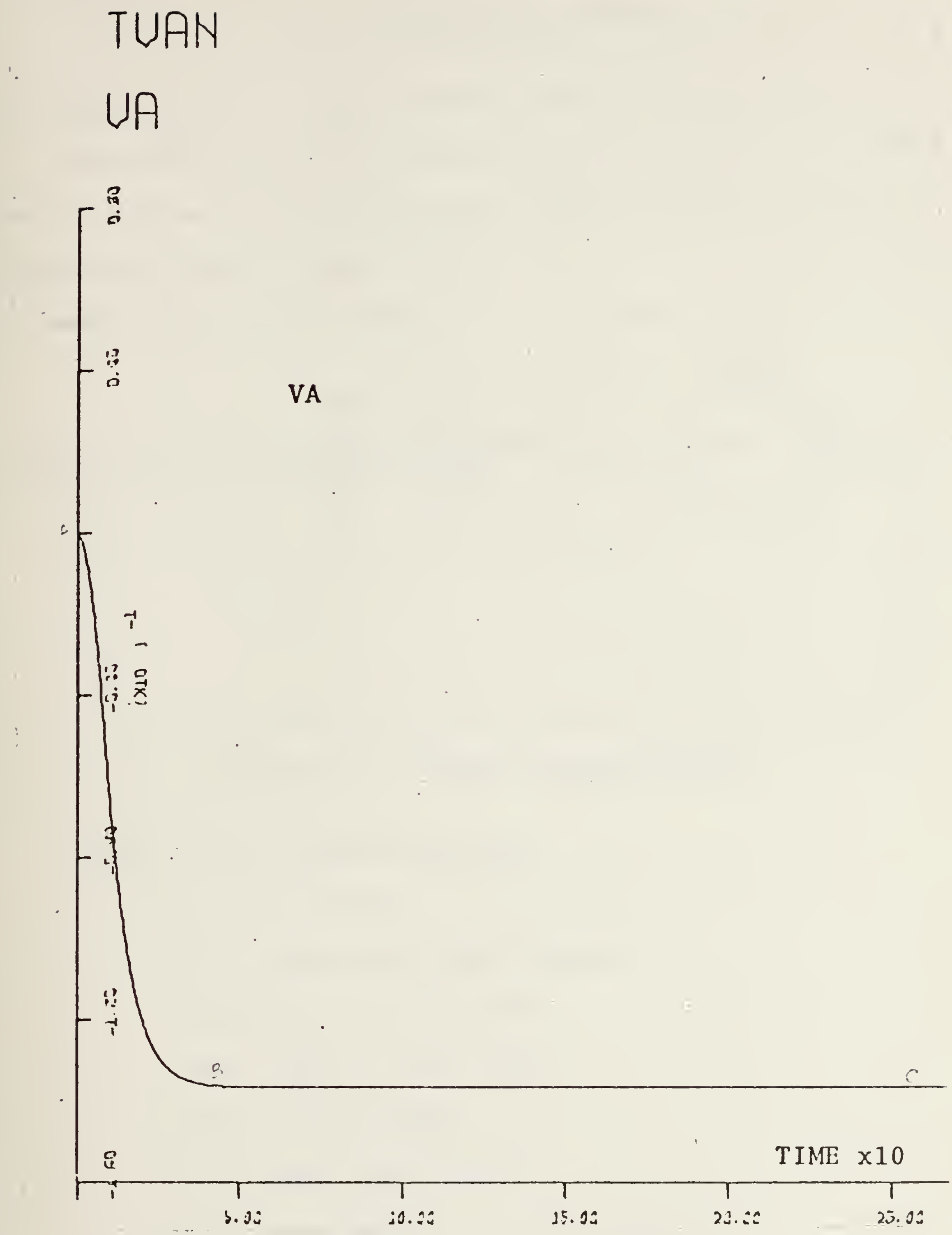



Figure D9. Angular Velocity about Y Axis.

## VI. SPEED CONTROL IN TURNS

### A. DYNAMIC BEHAVIOR OF THE PROPULSION PLANT:

The propulsion plant and turning path were observed. Now combine both of them and add feed-back of ship speed with Gain K1 in order to keep the ship speed constant in turns.

The block diagram for this part can be drawn:

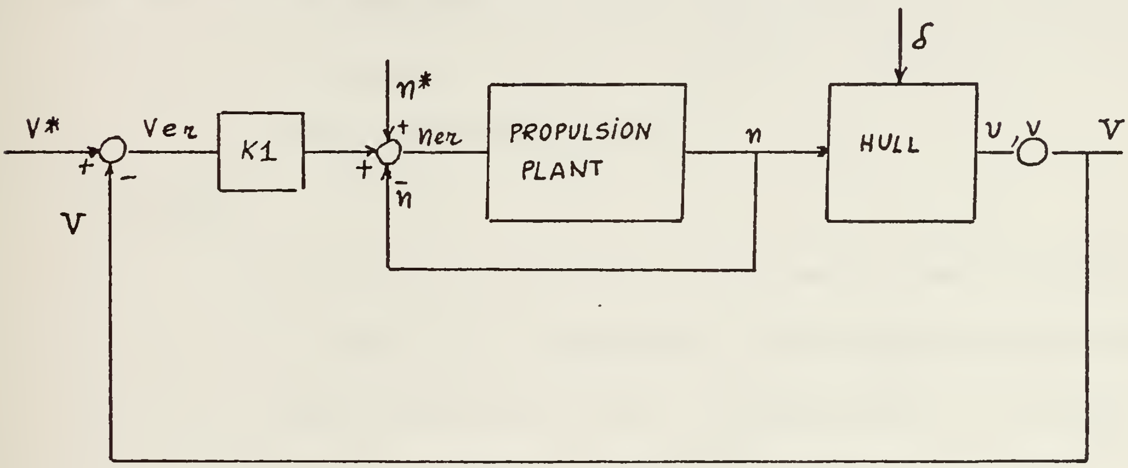



Figure E1. Feedback Control Velocity.

Where:

- V*: Reference ship speed.
- V : Ship speed.
- n*: Shaft angular speed command.
- U : Velocity about X axis.
- VA: Velocity about Y axis
- K1: Ship speed gain
- n : Shaft angular speed
- δ : Rudder angle

The block diagram of this system was shown in Appendix B.

## B. SIMULATION METHODS

1. Determine all initial conditions in the steady state

RUN 1.

Let propeller shaft speed command n* be constant

n* = 130 RPM

And no feedback of ship speed

K1 = 0

Then determine the steady state speeds (i.e., determine the component of initial condition ship speed on X axis and on Y axis (UIC, VIC).

RUN 2.

Now the propeller shaft speed command n*=130 rpm making K1 = 8,16,24,32 respectively. Then determine the steady state in each case (i.e., find all IC's in the steady state). This guarantees that the loop is in steady state, since the initial conditions on other variables might still cause a transient.

2. Put in a step change in the ship speed with 2 kts. increase and delay time 10 sec. Then V* becomes:

V* = 20. + 2.0 step (10.)

## C. SPEED CONTROL STUDIES

Using the inital conditions of RUN 1 and 2, a rudder command was applied at t = 0, causing a speed decrease due to added drag. At t = 10 sec, the commanded speed, V* was increased by 2 knots, stepwise. This caused a speed increase. The effects of changing the loop gain, K1, is shown in Figure E2.

D. DISCUSS THE CURVES

1. Ship resistance Rt, Wake fraction W, Thrust fraction t

The ship speed change was small, so that:

a. The ship resistance Rt = K.V (see Fig. B4) K = constant

then the form of Rt was the same as V (Fig. E3 curve 1)

b. The Wake fraction was constant (Fig. B1)

then W = (Fig. E3 curve 2)

c. In this interval the slope of the thrust fraction was negative. Then when V decreases to increases and as V increases t decreases (Fig. E3 curve 3)

2. σ curve, torque coefficient Cq, thrusting coefficient

$$VP = (1-W)\ V$$

$$= (1-.045)\ V$$

$$= .955\ V$$

and $$\sigma = \frac{nD}{Vp^2 - n^2 D^2}$$

The σ curve is shown in Fig. E4 curve 1

σ changed from .853 to .920 then the slope of Ct and Cq curve was constant. Then the Ct and Cq curve have the same form as the σ curve.

3. Propeller action torque Qp, shaft torque Qe and propeller angular speed n

$$Qp = Cq.p.D^3(VP^2+n^2D^2)$$

The Qp curve was shown in Fig. E5 curve 2.

The Wf curve and n curve are shown in Figures E6 and E7.

| | K1=0. | K1=8. | K1=16. | K1=24. | K1=32. |
|---|---|---|---|---|---|
| VIC | | 20.114 | 20.110 | 20.108 | 20.106 |
| VIC | -0.10446 | - 0.10446 | - 0.10446 | - 0.10446 | - 0.10446 |
| RIC | | 0.23219 | 0.23219 | 0.23219 | 0.23219 |
| NIC | | 2.2056 | 2.2055 | 2.2055 | 2.2055 |
| NRIC | | -242.28 | -454.09 | -665.58 | -876.55 |

TABLE 5 INITIAL CONDITIONS AT STEADY STATE

FOR K1=0,8,16,24,32

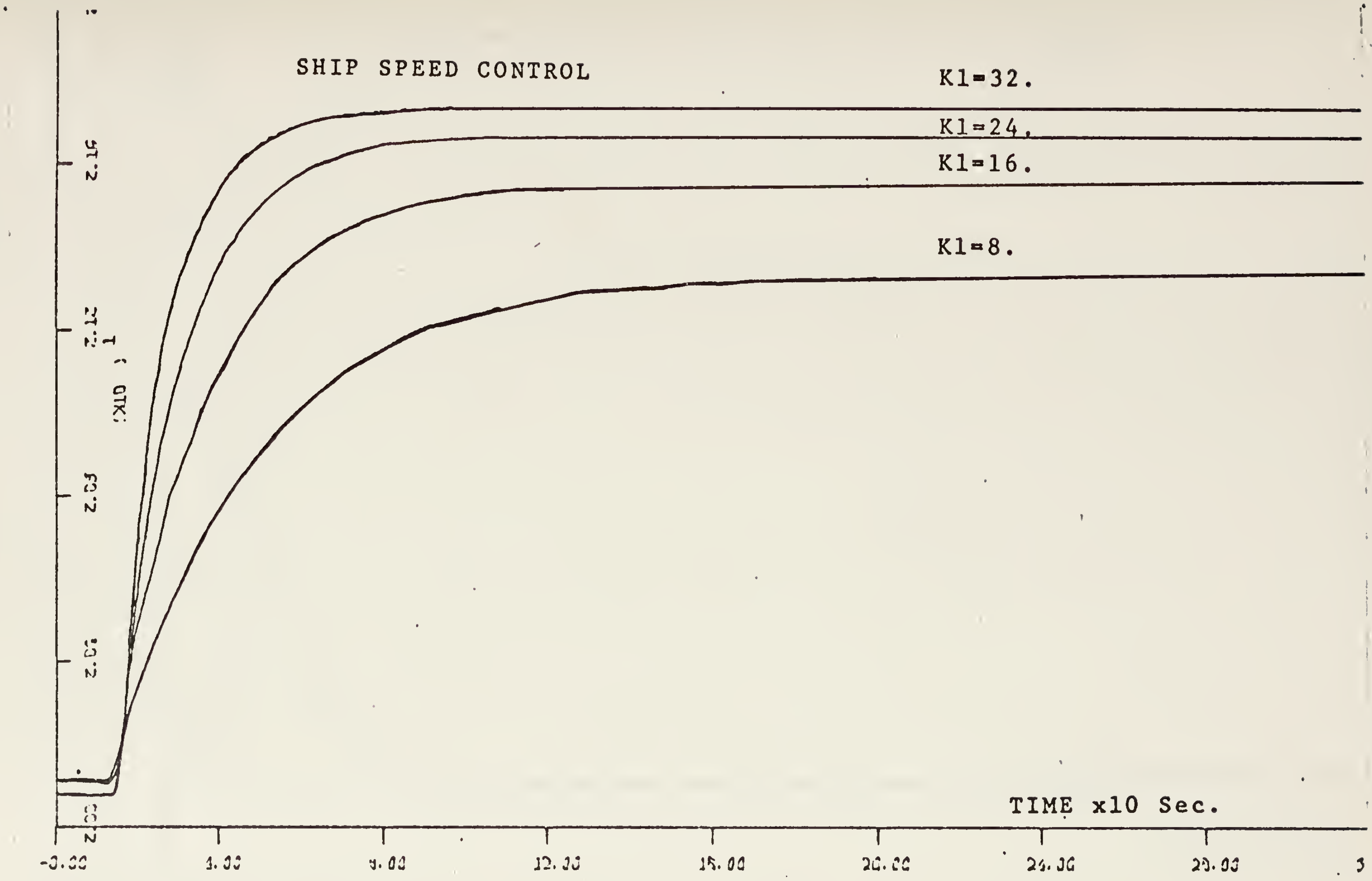



Figure E2. Ship Speed V versus Time, with K1 = 8,16,24,32.

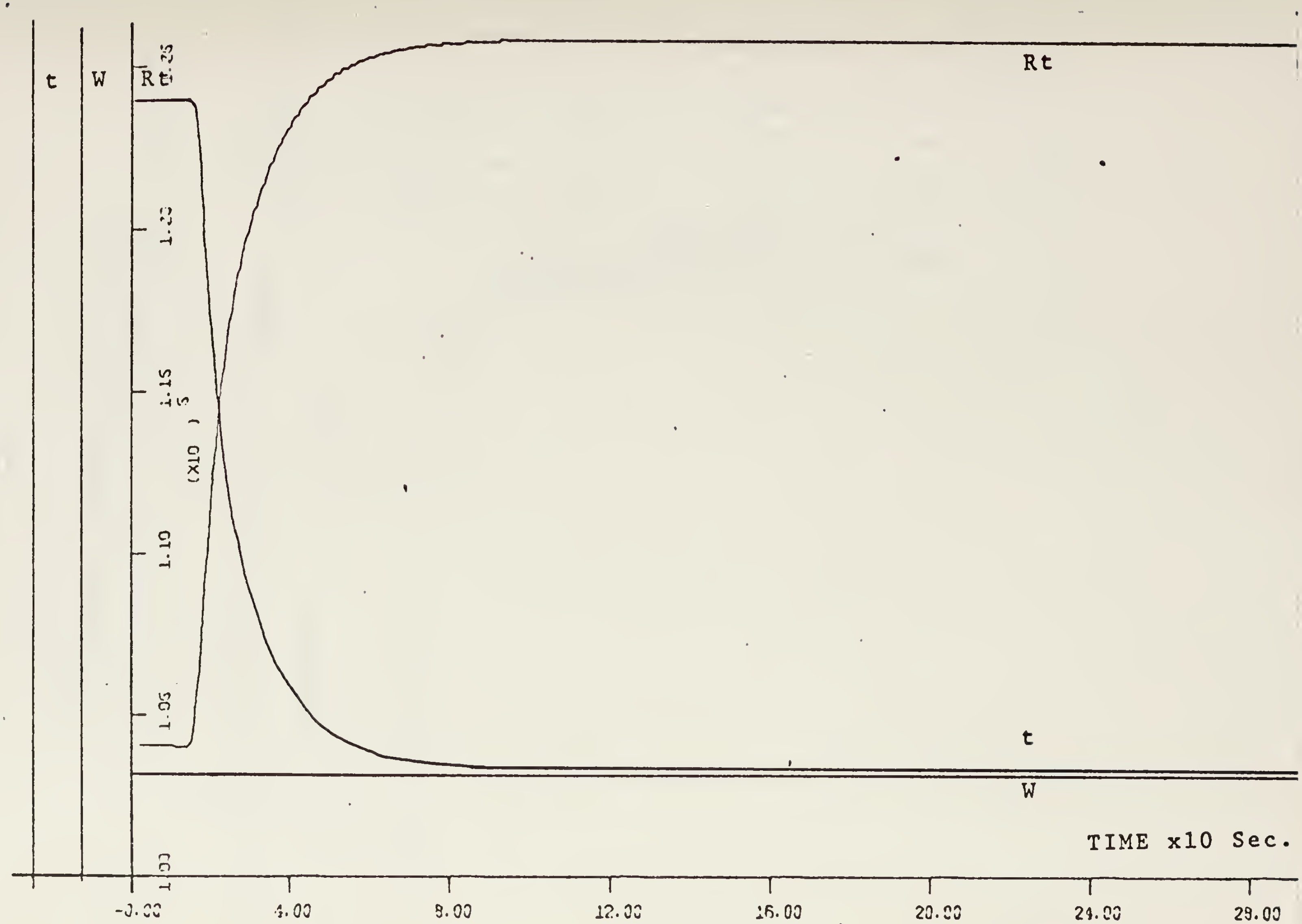



Figure E3. Ship resistance, Wake Fraction and Thrust Fraction versus Time.

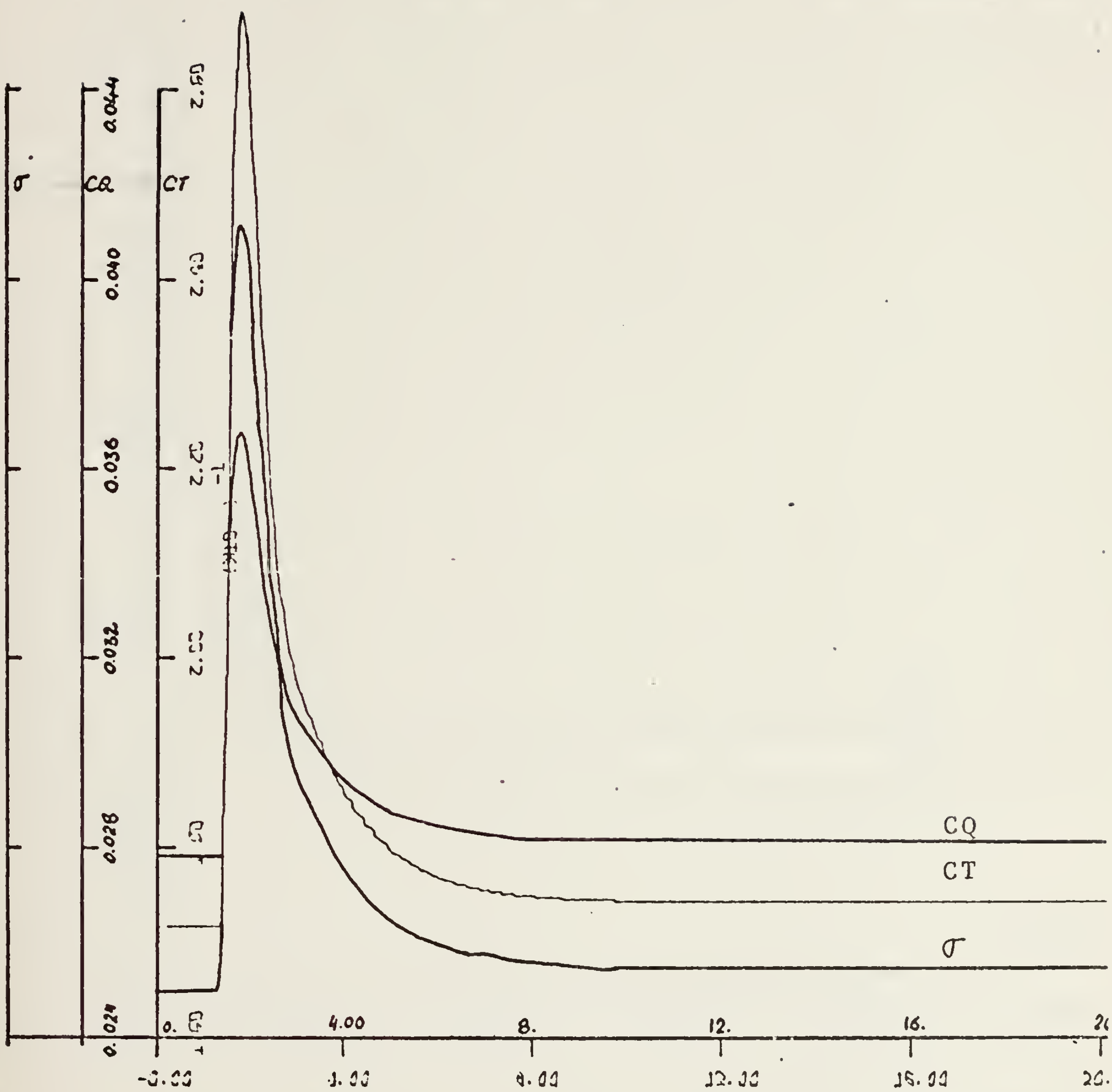



Figure E4. Second Modified Advance Coefficient , Torque Coefficient Cq, Thrust Coefficient Ct versus Time.

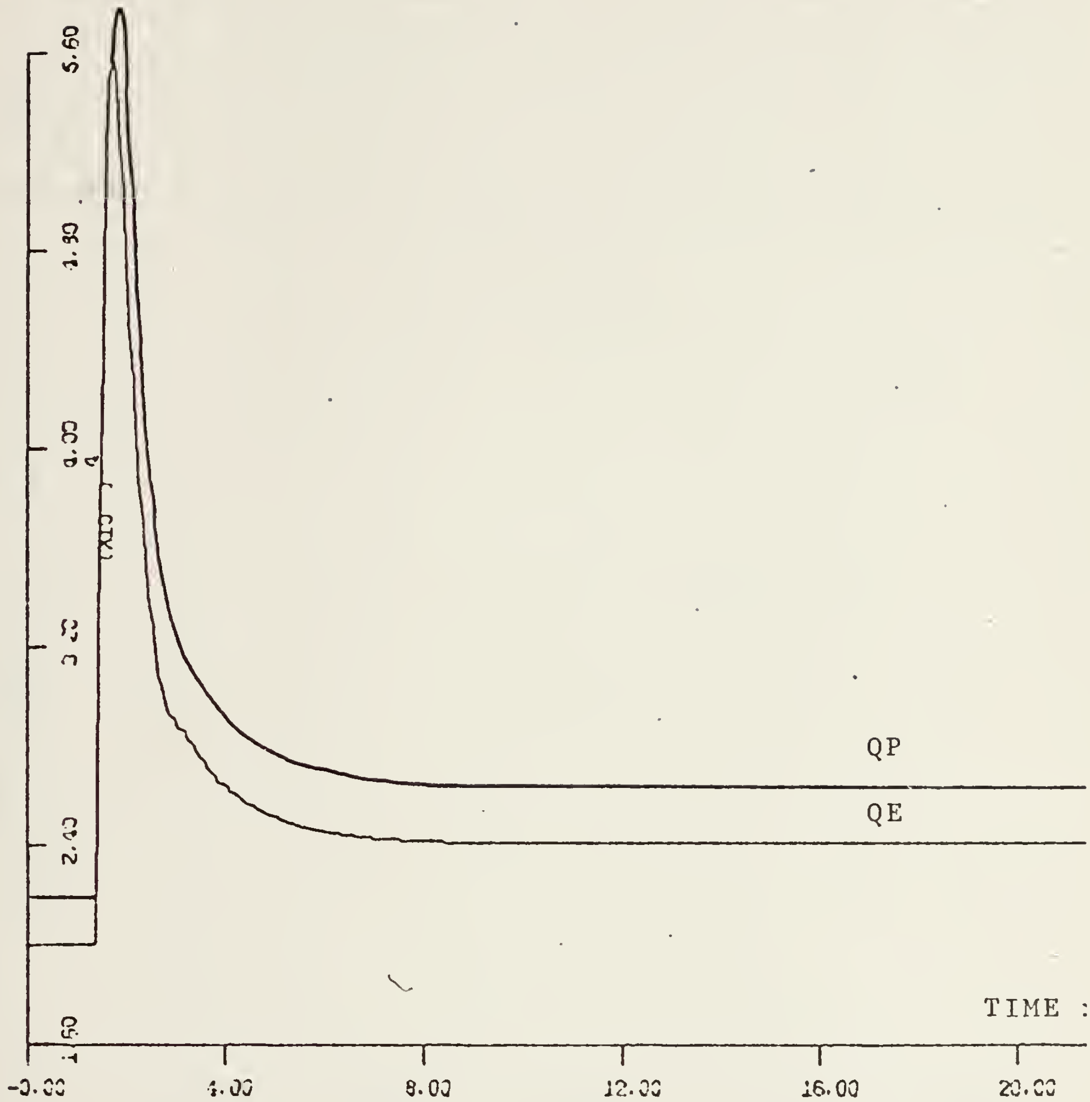



Figure E5. Propeller Action Torque Qp and Shaft Torque versus Time.

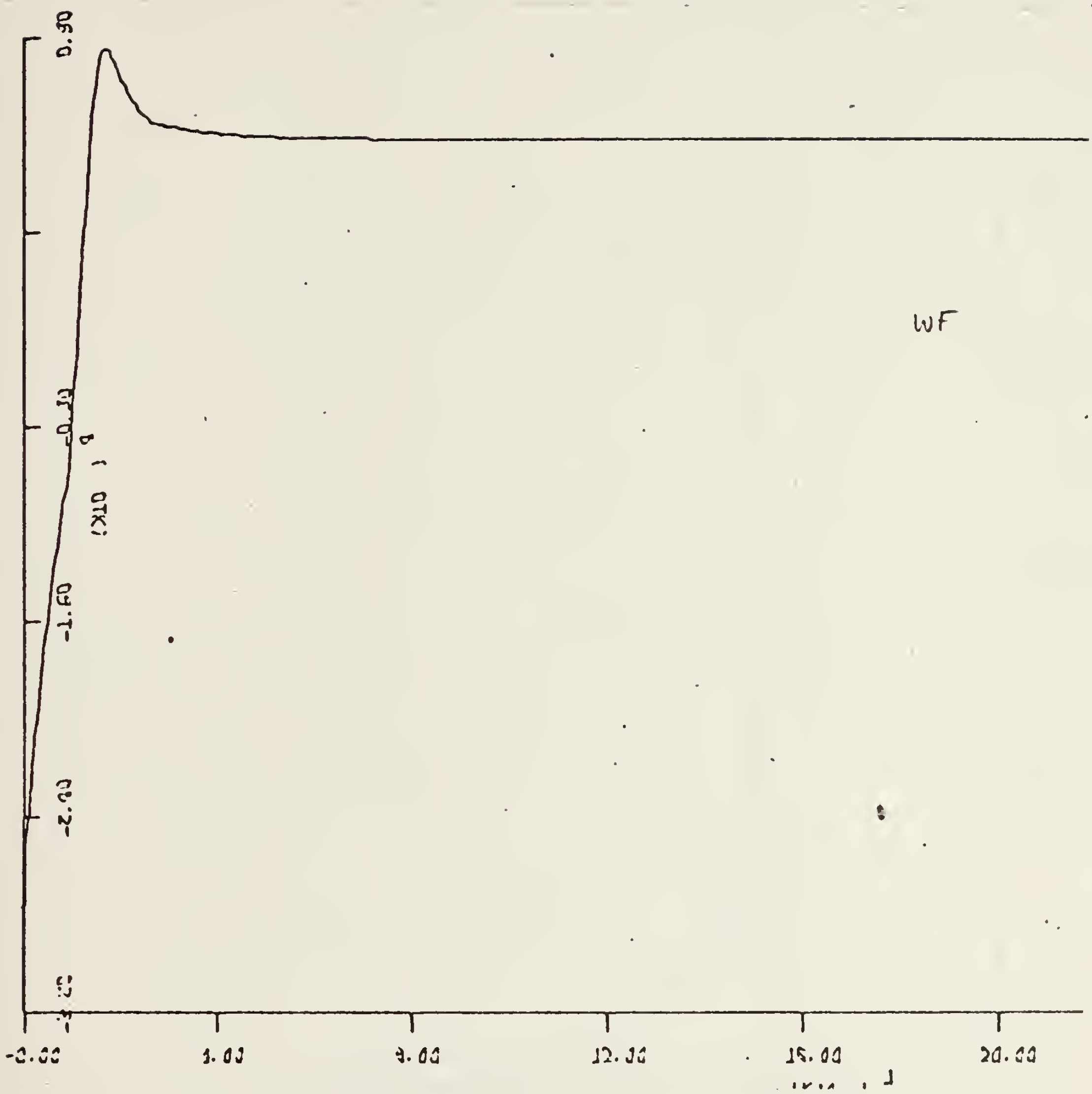



Figure E6. Fuel Flow Rate Wf versus Time.

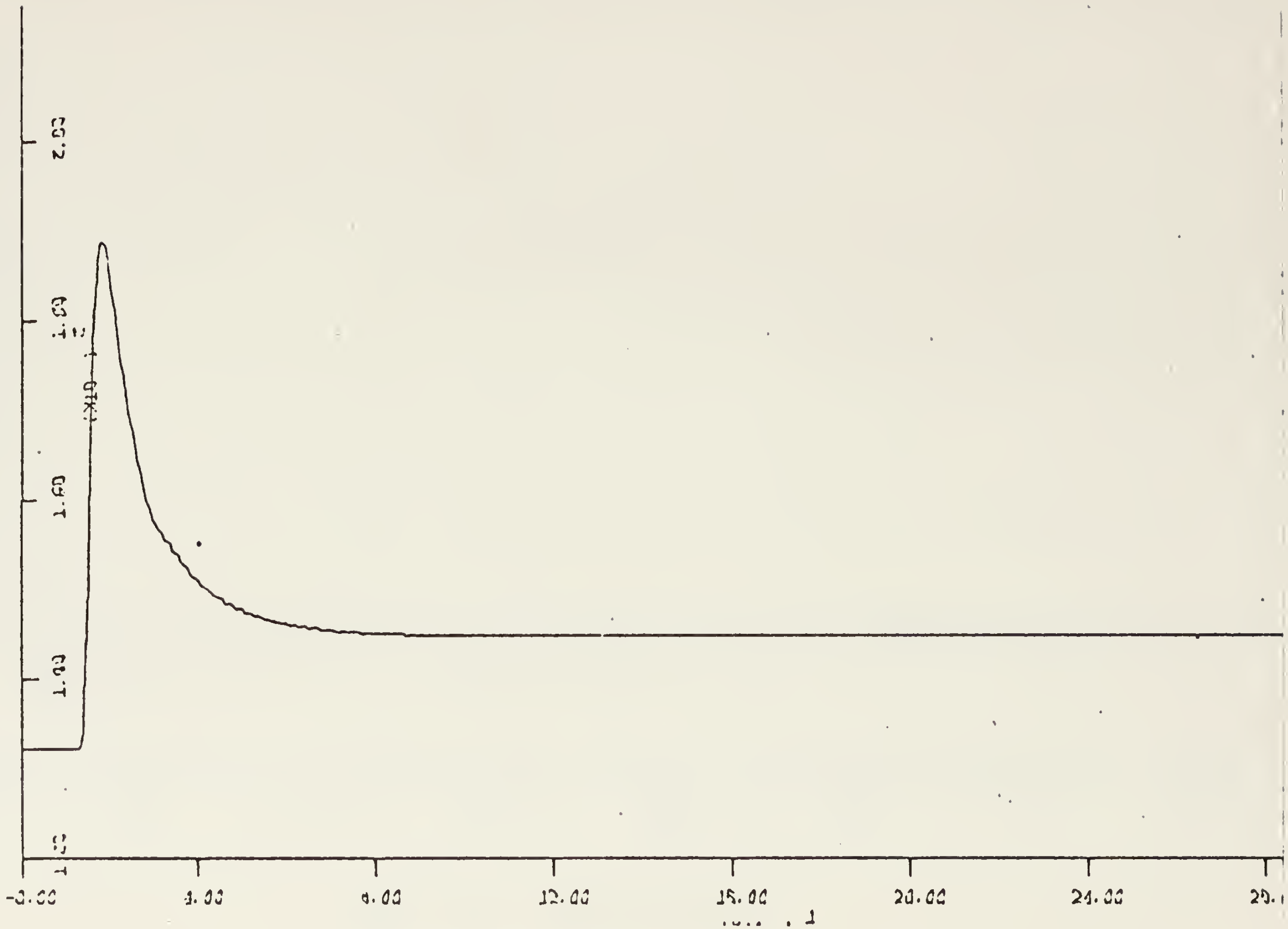


Figure E7. Propeller Angular Speed versus Time.

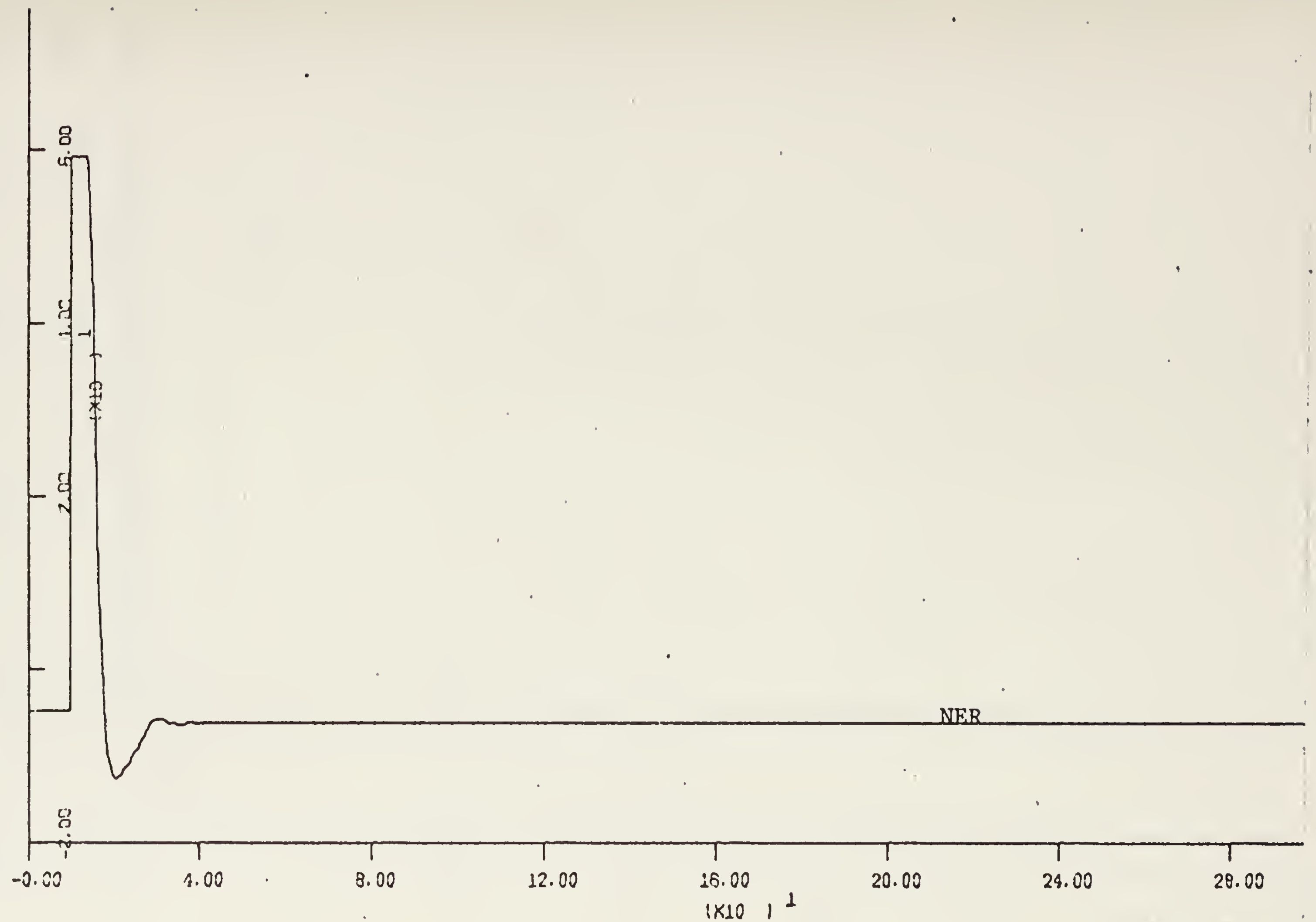



Figure E8. NER versus Time.

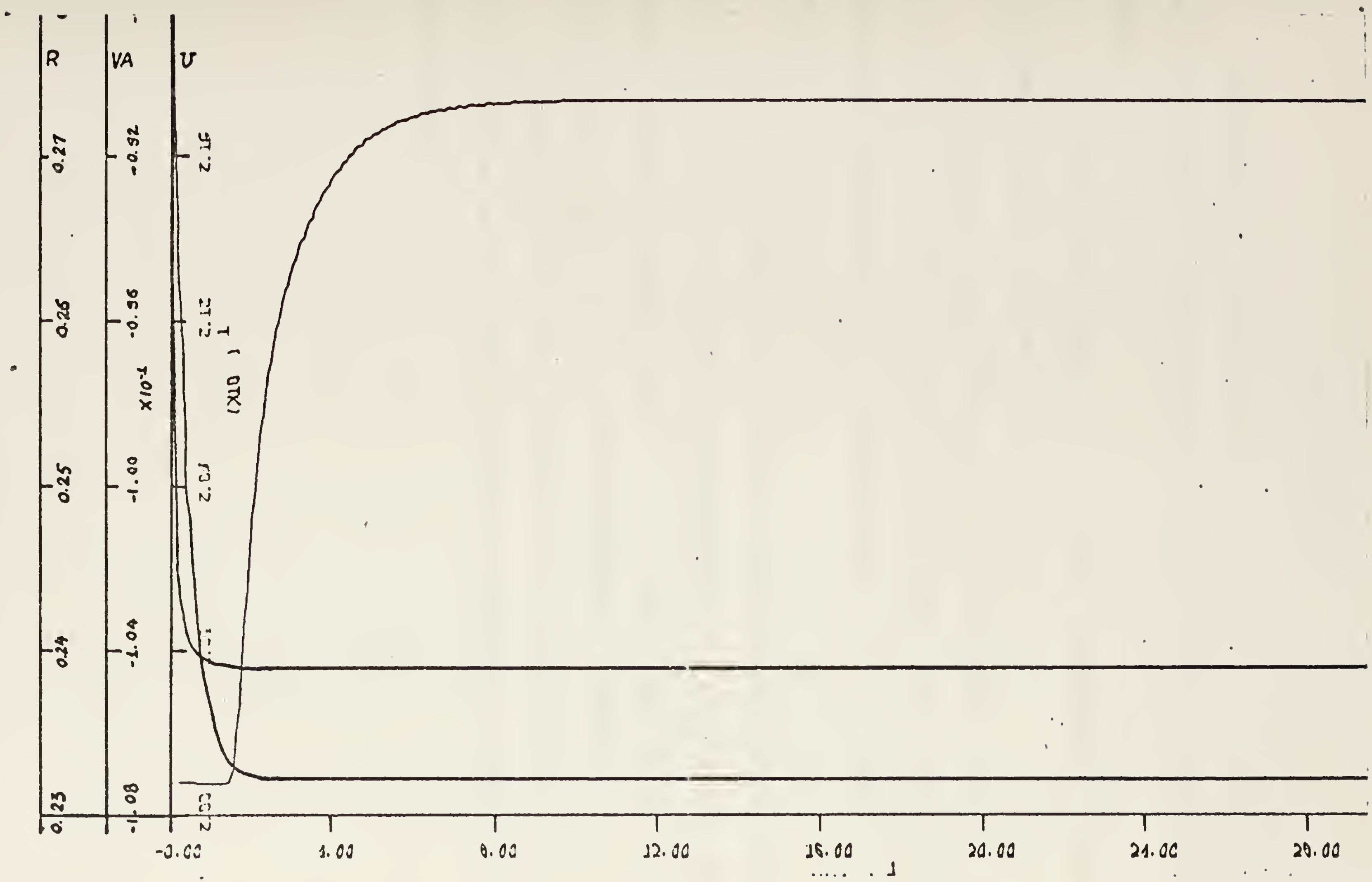



Figure E9. U, VA, R versus Time.

# VII. CONCLUSION

This thesis has presented the combined model of a propulsion plant and hull. DSL/360 LANGUAGE was found to be powerful for simulating ship motion.

In turbine powered ships, it is necessary to predict the propeller response to changes in power demand.

This problem has been investigated but the studies have been concentrated on the effect of dynamics of the ship. This work is concerned both with the dynamic of the propulsion plant and ship dynamics of the ship.

It has been shown that the complex, nonlinear dynamics of propulsion plant and hull can be adequately represented by an all digital computer model. The model permits studies of the internal dynamics of the propulsion plant, as well as the external dynamics of the hull.

It has been shown that the model can be incorporated in a feedback control system and its effects included in studies of control system performance.

# VIII. RECOMMENDATIONS

The combination of propulsion plant and hull in a single computer model provides a realistic tool for many studies. The following are topics suitable for future investigation.

a. Course keeping, station keeping and replenishment at sea.

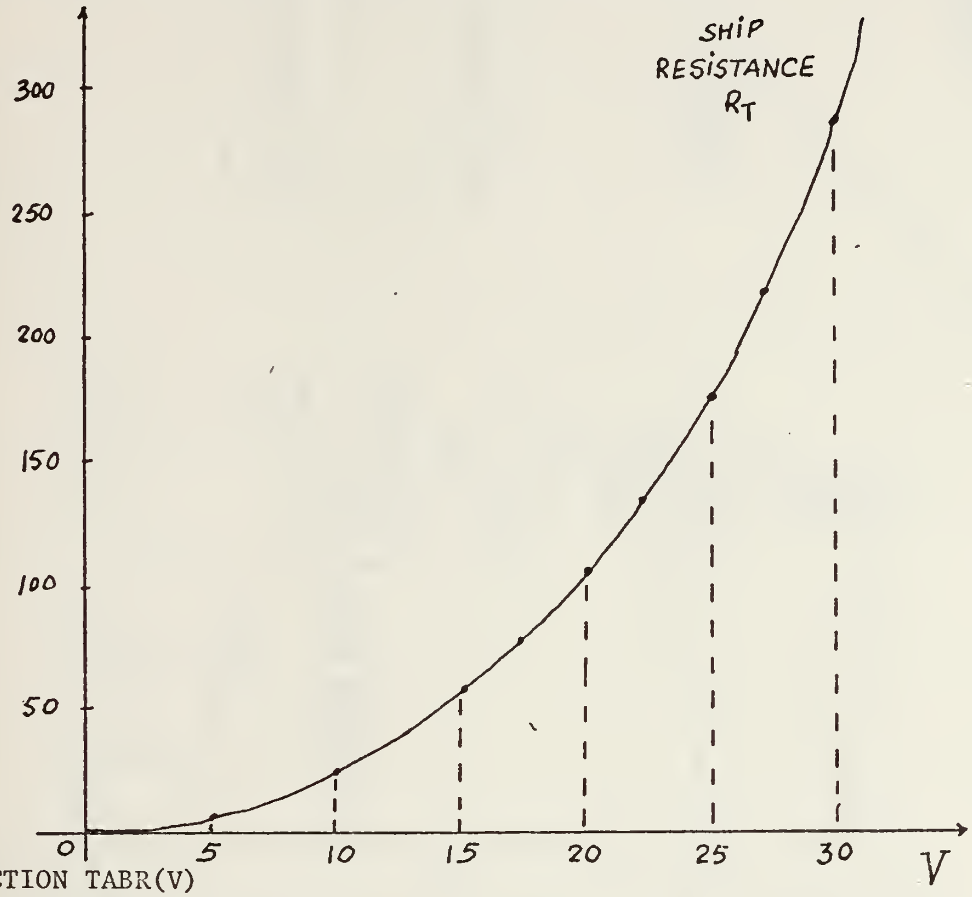
b. Effect of propulsion plant dynamics on maneuvering in sea states (or regular waves).

c. Effect of sea state conditions on the operation of the propulsion plant.

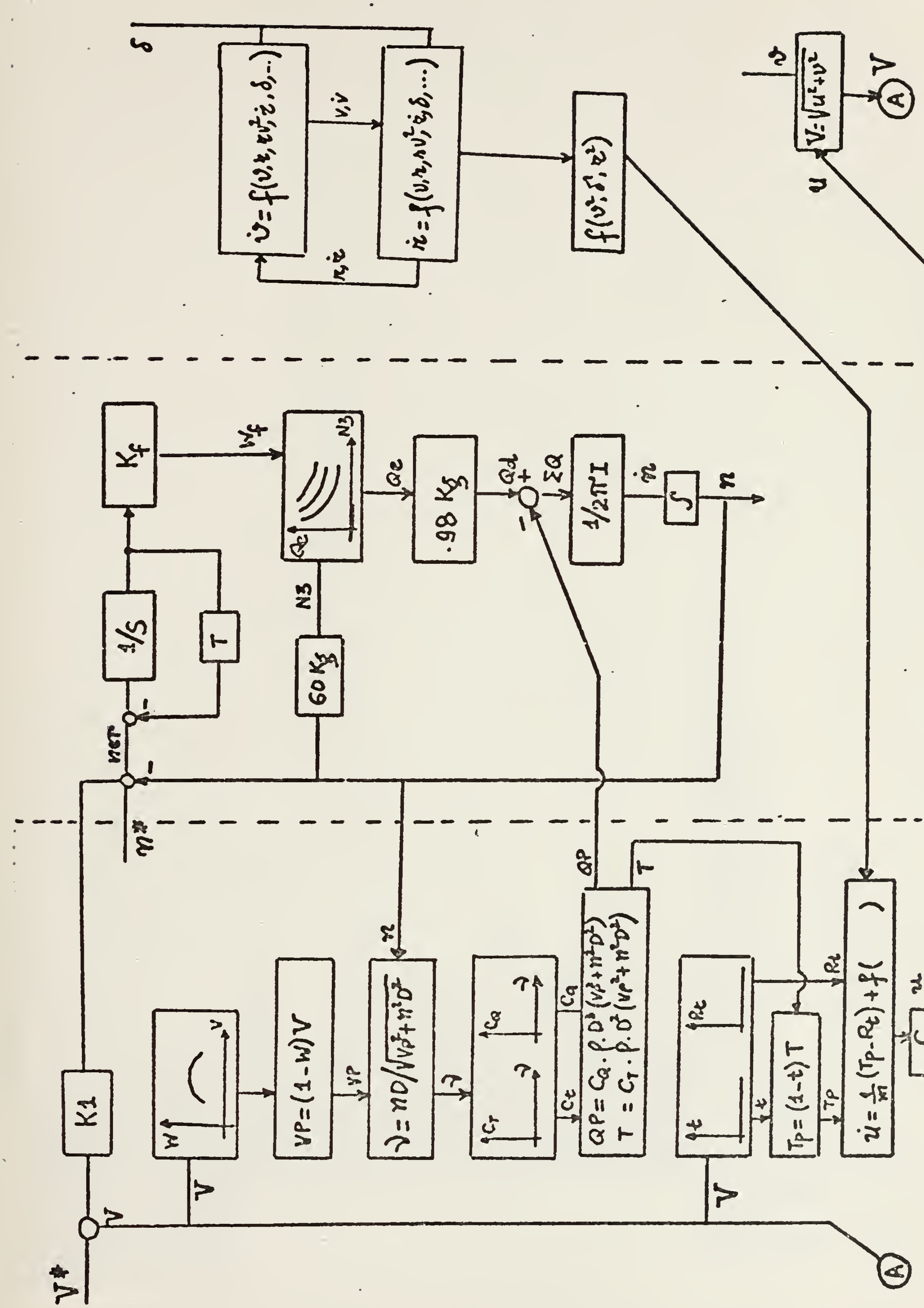
d. Discuss variation in steady state speed with increase command as shown in Fig. C1 - C5. Also discuss effect of governor loop on steady state speed, Fig. E2.

APPENDIX A

Table Look-up for Ship Resistance versus Speed:




```
FUNCTION TABR(V)
DIMENSION VT(13),RTT(13)
DATA VT/0.0,2.5,5.0,7.5,10.,12.5,15.,17.5,20.,22.5,25.5,127.5,30./
DATA RTT/2*0.0,7000.,13000.,25000.,39000.,57000.,80000.,1103000.,
136000.,173000.,225000.,280000./
IF(V.GT.30) GO TO 1
DELV 2.5
N IFIX(V/DELV) 1
SLOPR(RTT(N 1)-RTT(N))/(VT(N-1)-VT(N))
TABR SLOPR*(V-VT(N))-RTT(N)
RETURN
1 TABR 280000.
RETURN
END
```


K1
Kf
1/S
T
60 Kg
.98 Kg
1/2πI
VP=(1-W)V
V*
n*
A
V

```
*             COMPUTER PROGRAM  1
// EXEC DSL
//DSL.INPUT DD *
INTEG TRAPZ
INTGER NPLOT,NUM
CONST NPLOT=1
CONST KG=14.,PI=3.1416,I=9.80E4,P=2.0
CONST D=15.
CONST M=1.292E+6
INCON NIC=2.0
INCON UIC=15.
DERIVATIVE
      Y=STEP(0.0)
      WF=7000.+3000.*Y
      RT=TABR(V)
      W=TABW(V)
      T=TABT(V)
      VP=(1.-W)*V
      A=VP**2+(N*D)**2
      B=SQRT(A)
      S=(N*D)/B
      CT=TABCT(S,VP)
      TA=CT*P*D**2*A
      TP=(1.-T)*TA
      TPR=(TP-RT)/M
      UDOT=TPR
      U=INTGRL(UIC,UDOT)
      V=U
      CQ=TABCQ(S,VP)
      QP=CQ*P*D**3*A
      SUMQ=.98*KG*QE-QP
      NDOT=SUMQ/(2.*PI*I)
      N=INTGRL(NIC,NDOT)
      N4=60.*N
      N3=KG*N4
      QE=TABQE(N3,WF)
SAMPLE
PRINT 1.0,S,V,QP,QE,N4,SUMQ,CT,CQ,TPR
PREPAR 1.0,QE,N3,QP,CT,CQ,N4,V,TPR
CONTRL FINTIM=160.,DELT=1.0,DELS=1.0
GRAPH TIME,V
GRAPH TIME,QE
PRPLOT ONLY
      CALL DRWG(1,1,TIME,V)
      CALL DRWG(2,1,TIME,QE)
TERMINAL
      CALL ENDRW(NPLOT)
STOP
```

```
END
FORTRAN
      FUNCTION TABW(V)
      DIMENSION VT(13),WT(13)
      DATA VT/0.0,2.5,5.,7.5,10.,12.5,15.,17.5,20.,22.5,25.,27.5,30./
      DATA WT/4*0.0,.005,.01,.02,.033,.045,.045,.038,.02,.004/
      IF(V.GT.30.) GO TO 1
      DELV=2.5
      N=IFIX(V/DELV)+1
      SLOPW=(WT(N+1)-WT(N))/(VT(N+1)-VT(N))
      TABW=SLOPW*(V-VT(N))+WT(N)
      RETURN
 1    TABW=0.0
      RETURN
      END
      FUNCTION TABR(V)
      DIMENSION VT(13),RTT(13)
      DATA VT/0.0,2.5,5.,7.5,10.,12.5,15.,17.5,20.,22.5,25.,27.5,30./
      DATA RTT/2*0.0,7000.,13000.,25000.,39000.,57000.,80000.,103000.,
     1136000.,173000.,225000.,280000./
      IF(V.GT.30.) GO TO 1
      DELV=2.5
      N=IFIX(V/DELV)+1
      SLOPR=(RTT(N+1)-RTT(N))/(VT(N+1)-VT(N))
      TABR=SLOPR*(V-VT(N))+RTT(N)
      RETURN
 1    TABR=280000.
      RETURN
      END
      FUNCTION TABT(V)
      DIMENSION VT(13),TT(13)
      DATA VT/0.0,2.5,5.,7.5,10.,12.5,15.,17.5,20.,22.5,25.,27.5,30./
      DATA TT/5*0.0,.01,.05,.07,.08,.075,.072,.C6,.02/
      IF(V.GT.30.) GO TO 1
      DELV=2.5
      N=IFIX(V/DELV)+1
      SLOPT=(TT(N+1)-TT(N))/(VT(N+1)-VT(N))
      TABT=SLOPT*(V-VT(N))+TT(N)
      RETURN
 1    TABT=0.0
      RETURN
      END
      FUNCTION TABCT(S,VP)
      DIMENSION ST(21),CT1(21),CT2(21)
      DATA ST/-1.,-.9,-.8,-.7,-.6,-.5,-.4,-.3,-.2,-.1,0.,.1,.2,.3,
     1.4,.5,.6,.7,.8,.9,1./
      DATA CT2/-.40,-.15,-.C5,.05,.10,.15,.20,.26,.36,.44,.30,.31,.4,
     1.45,.42,.40,.39,.37,.32,.33,.50/
```

```
      DATA CT1/-.4,-.2,-.28,-.32,-.35,-.38,-.40,-.41,-.36,-.29,-.25,
     1-.35,-.34,-.25,-.20,-.13,-.05,.02,.10,.21,.45/
      DELS=0.1
      N=IFIX((S+1.)/DELS)+1
      IF(VP.LT.0.0) GO TO 2
      SLOCT1=(CT1(N+1)-CT1(N))/(ST(N+1)-ST(N))
       TABCT=SLOCT1*(S-ST(N))+CT1(N)
      GO TO 6
2     SLOCT2=(CT2(N+1)-CT2(N))/(ST(N+1)-ST(N))
       TABCT=SLOCT2*(S-ST(N))+CT2(N)
6     RETURN
      END
      FUNCTION TABCQ(S,VP)
      DIMENSION ST(21),CQ1(21),CQ2(21)
      DATA ST/-1.,-.9,-.8,-.7,-.6,-.5,-.4,-.3,-.2,-.1,0.,.1,.2,.3,
     1.4,.5,.6,.7,.8,.9,1./
      DATA CQ1/-.08,-.045,-.05,-.055,-.06,-.061,-.062,-.064,-.058,-.04,
     1-.037,-.055,-.05,-.035,-.028,-.015,-.008,.005,.02,.032,.07/
      DATA CQ2/-.08,-.035,-.015,0.0,.01,.02,.034,.042,.06,.07,.045,.05,
     1.068,.07,.07,.062,.06,.058,.058,.05,.08/
      DELS=0.1
      N=IFIX((S+1.)/DELS)+1
      IF(VP.LT.0.0) GO TO 2
      SLOCQ1=(CQ1(N+1)-CQ1(N))/(ST(N+1)-ST(N))
       TABCQ=SLOCQ1*(S-ST(N))+CQ1(N)
      GO TO 6
2     SLOCQ2=(CQ2(N+1)-CQ2(N))/(ST(N+1)-ST(N))
       TABCQ=SLOCQ2*(S-ST(N))+CQ2(N)
6     RETURN
      END
      FUNCTION TABQE(V3,WF)
      DIMENSION V3T(5),WFT(10),QET(5,10)
      V3T(1)=0.0
      V3T(2)=1000.
      V3T(3)=2000.
      V3T(4)=3000.
      V3T(5)=4000.
      WFT(1)=3300.
      WFT(2)=4300.
      WFT(3)=5300.
      WFT(4)=6300.
      WFT(5)=7300.
      WFT(6)=8300.
      WFT(7)=9300.
      WFT(8)=10300.
      WFT(9)=11300.
      WFT(10)=12300.
      QET(1,1)=20000.
```

```
QET(1,2)=28500.
QET(1,3)=37000.
QET(1,4)=45000.
QET(1,5)=53500.
QET(1,6)=62000.
QET(1,7)=70000.
QET(1,8)=77000.
QET(1,9)=86500.
QET(1,10)=95000.
QET(2,1)=12500.
QET(2,2)=20000.
QET(2,3)=27000.
QET(2,4)=34500.
QET(2,5)=41500.
QET(2,6)=48000.
QET(2,7)=54000.
QET(2,8)=59000.
QET(2,9)=64000.
QET(2,10)=69000.
QET(3,1)=8000.
QET(3,2)=13000.
QET(3,3)=18500.
QET(3,4)=24000.
QET(3,5)=29000.
QET(3,6)=34000.
QET(3,7)=39500.
QET(3,8)=45000.
QET(3,9)=50000.
QET(3,10)=55000.
QET(4,1)=5000.
QET(4,2)=9000.
QET(4,3)=13000.
QET(4,4)=17500.
QET(4,5)=22000.
QET(4,6)=26000.
QET(4,7)=30000.
QET(4,8)=34000.
QET(4,9)=38500.
QET(4,10)=43000.
QET(5,1)=3000.
QET(5,2)=6500.
QET(5,3)=10000.
QET(5,4)=13000.
QET(5,5)=17000.
QET(5,6)=20000.
QET(5,7)=24000.
QET(5,8)=27000.
QET(5,9)=30500.
```

```
      QET(5,10)=34000.
      IF(V3.LT.0.) GO TO 1
      IF(V3.GT.4000.) GO TO 2
      X3=V3
      GO TO 100
 1    X3=0.0
      GO TO 100
 2    X3=4000.
      GO TO 100
100   IF(WF.LT.3300.) GO TO 3
      IF(WF.GT.12300.) GO TO 4
      WF1=WF
      GO TO 200
 3    WF1=3300.
      GO TO 200
 4    WF1=12300.
200   I=IFIX(X3/1000.)+1
      J=IFIX((WF1-3300.)/1000.)+1
      DR=X3-V3T(I)
      DW=WF1-WFT(J)
      DELQR=(DR/1000.)*(QET(I+1,J)-QET(I,J))
      DELQW=(DW/1000.)*(QET(I,J+1)-QET(I,J))
      TABQE=QET(I,J)+DELQR+DELQW
      RETURN
      END
//PLOT.SYSIN DD *
 TVAN  N4
                                        8.        5.                          04
 TVAN  QE
                                        8.        5.                          04
```

```
*       COMPUTER PROGRAM    2
// EXEC DSL
//DSL.INPUT DD *
INTEG TRAPZ
INTGER NPLOT
INCON NIC=2.0
INCON UIC=15.
INCON NRIC=120.
CONST NPLOT=2
CONST KG=14.,PI=3.1416,I=9.80E4,P=2.0
CONST M=1.292E+6
CONST KF=40.
CONST D=15.
CONST T=100.
DERIVATIVE
      Y=STEP(0.0)
      NSTAR=120.+10.*Y
      NER=NSTAR-N4
      NDER=NER-T*NR
      NR=INTGRL(NRIC,NDER)
      DELF=KF*NR
      WF=7000.+DELF
      RT=TABR(V)
      W=TABW(V)
      T=TABT(V)
      VP=(1.-W)*V
      A=VP**2+(N*D)**2
      B=SQRT(A)
      S=(N*D)/B
      CT=TABCT(S,VP)
      TA=CT*P*D**2*A
      TP=(1.0-T)*TA
      TPR=(TP-RT)/M
       UDOT=TPR
      U=INTGRL(UIC,UDOT)
      V=U
      CQ=TABCQ(S,VP)
      QP=CQ*P*D**3*A
      SUMQ=.98*KG*QE-QP
      NDOT=SUMQ/(2.*PI*I)
      N=INTGRL(NIC,NDOT)
      N4=60.*N
      N3=KG*N4
      QE=TABQE(N3,WF)
SAMPLE
PRINT 1.0,TPR,CQ,CT,N4,QE,QP,V
PREPAR 1.0,QE,N3,QP,CT,CQ,N4,V,TPR
CONTRL FINTIM=160.,DELT=0.5,DELS=0.5
```

```
GRAPH TIME,N4
GRAPH TIME,QE
PRPLOT ONLY
      CALL DRWG(1,1,TIME,QE)
      CALL DRWG(2,1,TIME,N4)
TERMINAL
      CALL ENDRW(NPLOT)
STOP
END
FORTRAN
      FUNCTION TABT(V)
      DIMENSION VT(13),TT(13)
      DATA VT/0.0,2.5,5.,7.5,10.,12.5,15.,17.5,20.,22.5,25.,27.5,30./
      DATA TT/5*0.0,.01,.05,.07,.08,.075,.072,.06,.02/
      DELV=2.5
      N=IFIX(V/DELV)+1
      SLOPT=(TT(N+1)-TT(N))/(VT(N+1)-VT(N))
      TABT=SLOPT*(V-VT(N))+TT(N)
      RETURN
      END
      FUNCTION TABR(V)
      DIMENSION VT(13),RTT(13)
      DATA VT/0.0,2.5,5.,7.5,10.,12.5,15.,17.5,20.,22.5,25.,27.5,30./
      DATA RTT/2*0.0,7000.,13000.,25000.,39000.,57000.,80000.,103000.,
     1136000.,173000.,225000.,280000./
      DELV=2.5
      N=IFIX(V/DELV)+1
      SLOPR=(RTT(N+1)-RTT(N))/(VT(N+1)-VT(N))
      TABR=SLOPR*(V-VT(N))+RTT(N)
      RETURN
      END
      FUNCTION TABW(V)
      DIMENSION VT(13),WT(13)
      DATA VT/0.0,2.5,5.,7.5,10.,12.5,15.,17.5,20.,22.5,25.,27.5,30./
      DATA WT/4*0.0,.005,.01,.02,.033,.045,.045,.038,.02,.004/
      DELV=2.5
      N=IFIX(V/DELV)+1
      SLOPW=(WT(N+1)-WT(N))/(VT(N+1)-VT(N))
      TABW=SLOPW*(V-VT(N))+WT(N)
      RETURN
      END
      FUNCTION TABCQ(S,VP)
      DIMENSION ST(21),CQ1(21),CQ2(21)
      DATA ST/-1.,-.9,-.8,-.7,-.6,-.5,-.4,-.3,-.2,-.1,0.,.1,.2,.3,
     1.4,.5,.6,.7,.8,.9,1./
      DATA CQ1/-.08,-.045,-.05,-.055,-.06,-.061,-.062,-.064,-.058,-.04,
     1-.037,-.055,-.05,-.035,-.028,-.015,-.008,.005,.02,.032,.07/
      DATA CQ2/-.08,-.035,-.015,0.0,.01,.02,.034,.042,.06,.07,.045,.05,
```

```
     1.068,.07,.07,.062,.06,.058,.058,.05,.08/
      DELS=0.1
      N=IFIX((S+1.)/DELS)+1
      IF(VP.LT.0.0) GO TO 2
      SLOCQ1=(CQ1(N+1)-CQ1(N))/(ST(N+1)-ST(N))
       TABCQ=SLOCQ1*(S-ST(N))+CQ1(N)
      GO TO 6
2     SLOCQ2=(CQ2(N+1)-CQ2(N))/(ST(N+1)-ST(N))
       TABCQ=SLOCQ2*(S-ST(N))+CQ2(N)
6     RETURN
      END
      FUNCTION TABCT(S,VP)
      DIMENSION ST(21),CT1(21),CT2(21)
      DATA ST/-1.,-.9,-.8,-.7,-.6,-.5,-.4,-.3,-.2,-.1,0.,.1,.2,.3,
     1.4,.5,.6,.7,.8,.9,1./
      DATA CT2/-.40,-.15,-.C5,.05,.10,.15,.20,.26,.36,.44,.30,.31,.4,
     1.45,.42,.40,.39,.37,.32,.33,.50/
      DATA CT1/-.4,-.2,-.28,-.32,-.35,-.38,-.40,-.41,-.36,-.29,-.25,
     1-.35,-.34,-.25,-.20,-.13,-.05,.02,.10,.21,.45/
      DELS=0.1
      N=IFIX((S+1.)/DELS)+1
      IF(VP.LT.0.0) GO TO 2
      SLOCT1=(CT1(N+1)-CT1(N))/(ST(N+1)-ST(N))
       TABCT=SLOCT1*(S-ST(N))+CT1(N)
      GO TO 6
2     SLOCT2=(CT2(N+1)-CT2(N))/(ST(N+1)-ST(N))
       TABCT=SLOCT2*(S-ST(N))+CT2(N)
6     RETURN
      END
      FUNCTION TABQE(V3,WF)
      DIMENSION V3T(5),WFT(10),QET(5,10)
      V3T(1)=0.0
      V3T(2)=1000.
      V3T(3)=2000.
      V3T(4)=3000.
      V3T(5)=4000.
      WFT(1)=3300.
      WFT(2)=4300.
      WFT(3)=5300.
      WFT(4)=6300.
      WFT(5)=7300.
      WFT(6)=8300.
      WFT(7)=9300.
      WFT(8)=10300.
      WFT(9)=11300.
      WFT(10)=12300.
      QET(1,1)=20000.
      QET(1,2)=28500.
```

```
QET(1,3)=37000.
QET(1,4)=45000.
QET(1,5)=53500.
QET(1,6)=62000.
QET(1,7)=70000.
QET(1,8)=77000.
QET(1,9)=86500.
QET(1,10)=95000.
QET(2,1)=12500.
QET(2,2)=20000.
QET(2,3)=27000.
QET(2,4)=34500.
QET(2,5)=41500.
QET(2,6)=48000.
QET(2,7)=54000.
QET(2,8)=59000.
QET(2,9)=64000.
QET(2,10)=69000.
QET(3,1)=8000.
QET(3,2)=13000.
QET(3,3)=18500.
QET(3,4)=24000.
QET(3,5)=29000.
QET(3,6)=34000.
QET(3,7)=39500.
QET(3,8)=45000.
QET(3,9)=50000.
QET(3,10)=55000.
QET(4,1)=5000.
QET(4,2)=9000.
QET(4,3)=13000.
QET(4,4)=17500.
QET(4,5)=22000.
QET(4,6)=26000.
QET(4,7)=30000.
QET(4,8)=34000.
QET(4,9)=38500.
QET(4,10)=43000.
QET(5,1)=3000.
QET(5,2)=6500.
QET(5,3)=10000.
QET(5,4)=13000.
QET(5,5)=17000.
QET(5,6)=20000.
QET(5,7)=24000.
QET(5,8)=27000.
QET(5,9)=30500.
QET(5,10)=34000.
```

```
      IF(WF.LE.3300.) WF=3300.
      IF(WF.GE.12100.) WF=12100.
      IF(V3.LE.0.0) V3=0.0
      IF(V3.GE.4000.) V3=4000.
      I=IFIX(V3/1000.)+1
      J=IFIX((WF-3300.)/1000.)+1
      IF(I.GT.5)I=5
      IF(J.GT.10)J=10
      IF((I.EQ.5).OR.(J.EQ.10)) GO TO 1
      DR=V3-V3T(I)
      DW=WF-WFT(J)
      DELQR=(DR/1000.)*(QET(I+1,J)-QET(I,J))
      DELQW=(DW/1000.)*(QET(I,J+1)-QET(I,J))
      TABQE=QET(I,J)+DELQR+DELQW
      RETURN
    1 TABQE=QET(I,J)
      RETURN
      END
//PLCT.SYSIN DD *
 TVAN QE                                                           04
                                        8.         6.
 TVAN N42                                                          05
0.0        20.        120.       20.        8.         6.
```

```
*                 COMPUTER PROGRAM        3
//TVAN3  JOB (1345,0536,NE24),'TVAN',TIME=1
// EXEC DSL
//DSL.INPUT DD *
INTEG TRAPZ
INTGER NPLOT,NUM
CONST NPLOT=1
CONST TDMAX=20.,DRATE=40.
CONST N5=-.101,N6=-1.42,N7=-.024,N8=.0202,N9=0.0
CONST N0=-.0003,N1=-.075,N2=-.385,N3=-.306,N4=-.0569
CONST Y5=-.0461,Y6=-.0994,Y7=.05,Y8=0.0,Y9=.309
CONST Y0=.00016,Y1=-.260,Y2=-2.15,Y3=-1.18,Y4=-.0781
INCON XIC=0.0,YIC=0.0,VIC=0.0,RIC=0.0
INCON UIC=15.
INCON PHIC=0.0
INITIAL
         DETA=Y9*N8-N9*Y8
DERIVATIVE
         D=-DRATE*(RAMP(0.0)-RAMP(TDMAX/DRATE))/57.3
         U=INTGRL(UIC,UDOT)
         VA=INTGRL(VIC,VDOT)
         R=INTGRL(RIC,RDOT)
         PHI=INTGRL(PHIC,R)
         F1C=Y0+Y1*VA+Y2*VA**3+Y3*VA*R*R+Y4*R+Y5*R**3+Y6*R*VA*VA+Y7*D
         F2C=N0+N1*VA+N2*VA**3+N3*VA*R*R+N4*R+N5*R**3+N6*R*VA*VA+N7*D
         NUMV=N8*F1C-Y8*F2C
         NUMR=Y9*F2C-N9*F1C
         VDOT=NUMV/DETA
         RDOT=NUMR/DETA
         XDOT=U*COS(PHI)-VA*SIN(PHI)
         YDOT=U*SIN(PHI)+VA*COS(PHI)
         X=INTGRL(XIC,XDOT)
         Y=INTGRL(YIC,YDOT)
SAMPLE
PRINT .2,X,Y,PHI,VA,R,VDOT,RDOT
PREPAR 0.2,X,Y,PHI,VDOT,RDOT,VA,R
CONTRL FINTIM=39.,DELT=0.01,DELS=0.02
         CALL DRWG(1,1,X,Y)
TERMINAL
         CALL ENDRW(NPLOT)
END
STOP
//PLOT.SYSIN DD *
 TVAN U=1.0  20 DEGREE OF RUDDER ANGLES                                          05
-4.          2.1          -.5          2.1          5.          5.
```

```
*           COMPUTER PROGRAM    4
//TVAN12 JOB (1345,0536,NE24),'TVAN',TIME=5
// EXEC DSL
//DSL.INPUT DD *
INTEG TRAPZ
INTGER NPLOT,NUM
CONST NPLOT=1
CONST KG=14.,PI=3.1416,I=9.80E4,P=2.0
CONST M=1.292E+6
CONST KF=40.
CONST DA=15.
CONST T=5.
CONST TDMAX=20.,DRATE=40.,L=400.
CONST C10=-.189,C20=-.02,C30=.168,C40=-.177
CONST N5=-.101,N6=-1.42,N7=-.024,N8=.0202,N9=0.0
CONST N0=-.0003,N1=-.075,N2=-.385,N3=-.306,N4=-.0569
CONST Y5=-.0461,Y6=-.0994,Y7=.05,Y8=0.0,Y9=.309
CONST Y0=.00016,Y1=-.260,Y2=-2.15,Y3=-1.18,Y4=-.0781
CONST K1=32.
INCON NRIC=-862.84
INCON NIC=2.2049
INCON UIC=20.079
INCON RIC=0.23219
INCON VIC=-.10446
INCON XIC=0.0,YIC=0.0,PHIC=0.0
INITIAL
      NUM=0
      DETA=Y9*N8-N9*Y8
DERIVATIVE
      YA=STEP(10.0)
      NSTAR=130.
      NER=NSTAR-N40+KVER
      NDER=NER-T*NR
      NR=INTGRL(NRIC,NDER)
      DELF=KF*NR
      WF=7000.+DELF
      RT=TABR(V)
      W=TABW(V)
      T=TABT(V)
      VP=(1.-W)*V
      A=VP**2+(N*DA)**2
      B=SQRT(A)
      S=(N*DA)/B
      CT=TABCT(S,VP)
      TA=CT*P*DA**2*A
      TP=(1.0-T)*TA
      TPR=(TP-RT)/M
      UDOT=TPR
```

```
      U=INTGRL(UIC,UDOT)
      CQ=TABCQ(S,VP)
      QP=CQ*P*DA**3*A
      SUMQ=.98*KG*QE-QP
      NDOT=SUMQ/(2.*PI*I)
      N=INTGRL(NIC,NDOT)
      N40=60.*N
      N30=KG*N40
      QE=TABQE(N3,WF)
      D=-DRATE*(RAMP(0.0)-RAMP(TDMAX/DRATE))/57.3
      VA=INTGRL(VIC,VDOT)
      R=INTGRL(RIC,RDOT)
      PHI=INTGRL(PHIC,R)
      F2C=N0+N1*VA+N2*VA**3+N3*VA*R*R+N4*R+N5*R**3+N6*R*VA*VA+N7*D
      F1C=Y0+Y1*VA+Y2*VA**3+Y3*VA*R*R+Y4*R+Y5*R**3+Y6*R*VA*VA+Y7*D
      NUMV=N8*F1C-Y8*F2C
      NUMR=Y9*F2C-N9*F1C
      VDOT=NUMV/DETA
      RDOT=NUMR/DETA
      XDOT=U*COS(PHI)-VA*SIN(PHI)
      YDOT=U*SIN(PHI)+VA*COS(PHI)
      Y=INTGRL(YIC,YDOT)
      X=INTGRL(XIC,XDOT)
      SQ=U**2+VA**2
      V=SQRT(SQ)
      YA1=STEP(10.0)
      VSTAR=20.+2.*YA1
       VER=VSTAR-V
      KVER=K1*VER
SAMPLE
CONTRL FINTIM=320.,DELT=0.5,DELS=0.5
PREPAR 0.5,QE,N4,WF,CQ,CT,QP,S,T,WT,RT
      CALL DRWG(1,1,TIME,WF)
      CALL DRWG(2,1,TIME,QE)
      CALL DRWG(3,1,TIME,N4)
      CALL DRWG(4,1,TIME,CQ)
      CALL DRWG(5,1,TIME,CT)
      CALL DRWG(6,1,TIME,QP)
      CALL DRWG(7,1,TIME,S)
TERMINAL
      CALL ENDRW(NPLOT)
STOP
END
FORTRAN
      FUNCTION TABW(V)
      DIMENSION VT(13),WT(13)
      DATA VT/0.0,2.5,5.,7.5,10.,12.5,15.,17.5,20.,22.5,25.,27.5,30./
      DATA WT/4*0.0,.005,.01,.02,.033,.045,.045,.038,.02,.004/
```

```
      IF(V.GT.30.) GO TO 1
      DELV=2.5
      N=IFIX(V/DELV)+1
      SLOPW=(WT(N+1)-WT(N))/(VT(N+1)-VT(N))
      TABW=SLOPW*(V-VT(N))+WT(N)
      RETURN
1     TABW=0.0
      RETURN
      END
      FUNCTION TABR(V)
      DIMENSION VT(13),RTT(13)
      DATA VT/0.0,2.5,5.,7.5,10.,12.5,15.,17.5,20.,22.5,25.,27.5,30./
      DATA RTT/2*0.0,7000.,13000.,25000.,39000.,57000.,80000.,103000.,
     1136000.,173000.,225000.,280000./
      IF(V.GT.30.) GO TO 1
      DELV=2.5
      N=IFIX(V/DELV)+1
      SLOPR=(RTT(N+1)-RTT(N))/(VT(N+1)-VT(N))
      TABR=SLOPR*(V-VT(N))+RTT(N)
      RETURN
1     TABR=280000.
      RETURN
      END
      FUNCTION TABT(V)
      DIMENSION VT(13),TT(13)
      DATA VT/0.0,2.5,5.,7.5,10.,12.5,15.,17.5,20.,22.5,25.,27.5,30./
      DATA TT/5*0.0,.01,.05,.07,.08,.075,.072,.06,.02/
      IF(V.GT.30.) GO TO 1
      DELV=2.5
      N=IFIX(V/DELV)+1
      SLOPT=(TT(N+1)-TT(N))/(VT(N+1)-VT(N))
      TABT=SLOPT*(V-VT(N))+TT(N)
      RETURN
1     TABT=0.0
      RETURN
      END
      FUNCTION TABCT(S,VP)
      DIMENSION ST(21),CT1(21),CT2(21)
      DATA ST/-1.,-.9,-.8,-.7,-.6,-.5,-.4,-.3,-.2,-.1,0.,.1,.2,.3,
     1.4,.5,.6,.7,.8,.9,1./
      DATA CT2/-.40,-.15,-.05,.05,.10,.15,.20,.26,.36,.44,.30,.31,.4,
     1.45,.42,.40,.39,.37,.32,.33,.50/
      DATA CT1/-.4,-.2,-.28,-.32,-.35,-.38,-.40,-.41,-.36,-.29,-.25,
     1-.35,-.34,-.25,-.20,-.13,-.05,.02,.10,.21,.45/
      DELS=0.1
      N=IFIX((S+1.)/DELS)+1
      IF(VP.LT.0.0) GO TO 2
      SLOCT1=(CT1(N+1)-CT1(N))/(ST(N+1)-ST(N))
```

```
        TABCT=SLOCT1*(S-ST(N))+CT1(N)
       GO TO 6
 2     SLOCT2=(CT2(N+1)-CT2(N))/(ST(N+1)-ST(N))
        TABCT=SLOCT2*(S-ST(N))+CT2(N)
 6     RETURN
       END
       FUNCTION TABCQ(S,VP)
       DIMENSION ST(21),CQ1(21),CQ2(21)
       DATA ST/-1.,-.9,-.8,-.7,-.6,-.5,-.4,-.3,-.2,-.1,0.,.1,.2,.3,
      1.4,.5,.6,.7,.8,.9,1./
       DATA CQ1/-.08,-.045,-.05,-.055,-.06,-.061,-.062,-.064,-.058,-.04,
      1-.037,-.055,-.05,-.035,-.028,-.015,-.008,.005,.02,.032,.07/
       DATA CQ2/-.08,-.035,-.015,0.0,.01,.02,.034,.042,.06,.07,.045,.05,
      1.068,.07,.07,.062,.06,.058,.058,.05,.08/
       DELS=0.1
       N=IFIX((S+1.)/DELS)+1
       IF(VP.LT.0.0) GO TO 2
       SLOCQ1=(CQ1(N+1)-CQ1(N))/(ST(N+1)-ST(N))
        TABCQ=SLOCQ1*(S-ST(N))+CQ1(N)
       GC TO 6
 2     SLOCQ2=(CQ2(N+1)-CQ2(N))/(ST(N+1)-ST(N))
        TABCQ=SLOCQ2*(S-ST(N))+CQ2(N)
 6     RETURN
       END
       FUNCTION TABQE(V3,WF)
       DIMENSION V3T(5),WFT(10),QET(5,10)
       V3T(1)=0.0
       V3T(2)=1000.
       V3T(3)=2000.
       V3T(4)=3000.
       V3T(5)=4000.
       WFT(1)=3300.
       WFT(2)=4300.
       WFT(3)=5300.
       WFT(4)=6300.
       WFT(5)=7300.
       WFT(6)=8300.
       WFT(7)=9300.
       WFT(8)=10300.
       WFT(9)=11300.
       WFT(10)=12300.
       QET(1,1)=20000.
       QET(1,2)=28500.
       QET(1,3)=37000.
       QET(1,4)=45000.
       QET(1,5)=53500.
       QET(1,6)=62000.
       QET(1,7)=70000.
```

```
      QET(1,8)=77000.
      QET(1,9)=86500.
      QET(1,10)=95000.
      QET(2,1)=12500.
      QET(2,2)=20000.
      QET(2,3)=27000.
      QET(2,4)=34500.
      QET(2,5)=41500.
      QET(2,6)=48000.
      QET(2,7)=54000.
      QET(2,8)=59000.
      QET(2,9)=64000.
      QET(2,10)=69000.
      QET(3,1)=8000.
      QET(3,2)=13000.
      QET(3,3)=18500.
      QET(3,4)=24000.
      QET(3,5)=29000.
      QET(3,6)=34000.
      QET(3,7)=39500.
      QET(3,8)=45000.
      QET(3,9)=50000.
      QET(3,10)=55000.
      QET(4,1)=5000.
      QET(4,2)=9000.
      QET(4,3)=13000.
      QET(4,4)=17500.
      QET(4,5)=22000.
      QET(4,6)=26000.
      QET(4,7)=30000.
      QET(4,8)=34000.
      QET(4,9)=38500.
      QET(4,10)=43000.
      QET(5,1)=3000.
      QET(5,2)=6500.
      QET(5,3)=10000.
      QET(5,4)=13000.
      QET(5,5)=17000.
      QET(5,6)=20000.
      QET(5,7)=24000.
      QET(5,8)=27000.
      QET(5,9)=30500.
      QET(5,10)=34000.
      IF(V3.LT.0.) GO TO 1
      IF(V3.GT.4000.) GO TO 2
      X3=V3
      GO TO 100
1     X3=0.0
```

```
      GC TO 100
 2    X3=4000.
      GC TO 100
 100  IF(WF.LT.3300.) GO TO 3
      IF(WF.GT.12300.) GO TO 4
      WF1=WF
      GO TO 200
 3    WF1=3300.
      GC TO 200
 4    WF1=12300.
 200  I=IFIX(X3/1000.)+1
      J=IFIX((WF1-3300.)/1000.)+1
      DR=X3-V3T(I)
      DW=WF1-WFT(J)
      DELQR=(DR/1000.)*(QET(I+1,J)-QET(I,J))
      DELQW=(DW/1000.)*(QET(I,J+1)-QET(I,J))
      TABQE=QET(I,J)+DELQR+DELQW
      RETURN
      END
//PLCT.SYSIN DD *
 TVAN WF
                                                                      04
                              8.        5.
 TVAN QE
                                                                      04
                              8.        5.
 TVAN N4
                                                                      04
                              8.        5.
 TVAN CQ
                                                                      04
                              8.        5.
 TVAN CT
                                                                      04
                              8.        5.
 TVAN QP
                                                                      04
                              8.        5.
 TVAN S
                                                                      04
                              8.        5.

PREPAR 0.5,V,U
      CALL DRWG(1,1,TIME,V)
CONST K1=32.
INCCN NRIC=-862.84
INCON NIC=2.2049
```

```
INCON UIC=20.079
INCON RIC=0.23219
INCON VIC=-.10446
INCON XIC=0.0,YIC=0.0,PHIC=0.0
CONST K1=24.
INCON NRIC=-665.58
INCON NIC=2.2055
INCON UIC=20.108
INCON VIC=-.10446
INCON RIC=.23219
INCON XIC=0.0,YIC=0.0,PHIC=0.0
CONST K1=16.
INCON NRIC=-454.09
INCON XIC=0.0,YIC=0.0,PHIC=0.0
INCON UIC=20.110
INCON RIC=0.23219
INCON NIC=2.2055
INCON VIC=-.10446
CONST K1=8.
INCON NIC=2.2056
INCON UIC=20.114
INCON NRIC=-242.28
INCON VIC=-0.10446,RIC=0.23219
INCON XIC=0.0,YIC=0.0,PHIC=0.0
```

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T7685 Tran-Van
c.1 Simulation of propulsion plant dynamics and their effect on speed control.